Indian Agriculture by 2047

A Roadmap for Research, Education and Extension

Himanshu Pathak • P.K. Joshi
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V.K. Baranwal • R.K. Jain

Editors

National Academy of Agricultural Sciences
New Delhi

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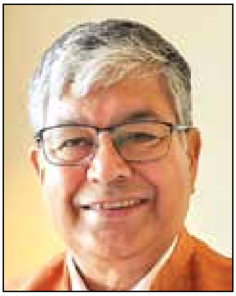
Dr. Himanshu Pathak is the Director General of International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India. He is also the President of National Academy of Agricultural Sciences (NAAS). Earlier, he served as Secretary, Department of Agricultural Research and Education, Govt. of India & Director General, Indian Council of Agricultural Research (ICAR); Director, ICAR-National Institute of Abiotic Stress Management, Baramati, Maharashtra and Director, ICAR-Central Rice Research Institute, Cuttack, Odisha. He is a scientist of global repute working on abiotic stresses, climate change, and soil science for more than 30 years. He has published more than 250 research papers and 15 books with an h-index of 84, i10-index of 280, and more than 28,500 citations. He is a Fellow of the prominent science Academies of the country (INSA, NASI and NAAS) and recipient of several national and international awards including, Rafi Ahmed Kidwai Award of ICAR, Humboldt Fellowship of Germany and BOYSCAST Fellowship of Govt. of India.

Dr. P.K. Joshi



Dr. P.K. Joshi superannuated as the Director-South Asia, International Food Policy Research Institute. Prior to this, he held the positions of Director, ICAR-National Academy of Agricultural Research Management, and Director ICAR-National Centre of Agricultural Economics and Policy Research. Presently, he is President of the Agricultural Economics Research Association (India), Vice-President of the National Academy of Agricultural Sciences, and Board of Directors of the Asia Pacific Agriculture Policy Forum (South Korea). He has extensively worked in the areas of technology policy, natural resource management, climate change, markets and institutional economics in India and many South and Southeast Asian countries. Dr. Joshi has received several awards and recognitions for his outstanding contribution in agricultural economics, policy research & management, and for demonstrating an exemplary role in providing leadership in the agricultural research system.

Dr. W.S. Lakra

Dr. W.S. Lakra graduated from University of Delhi and holds a D.Sc. degree with postdoc experience from CSIRO, Australia and Harvard University, USA. He has served as Director, National Bureau of Fish Genetic Resources, Lucknow, and Director and Vice Chancellor of the Central Institute of Fisheries Education, Mumbai. He has several awards and honors to his credit, including Dr. M.S. Swaminathan Best Indian Fisheries Scientist Award, Vasvik Award, Hari Om Ashram Trust Award of the Indian Council of Agricultural Research. He is an elected Fellow of the National Academy of Sciences, India, and the National Academy of Agricultural Sciences. His research areas include fisheries, aquaculture genetics, biotechnology, and biodiversity.

Dr. Ashok K. Singh

Dr. A.K. Singh is a renowned rice breeder and teacher par excellence for last 30 years at Indian Agricultural Research Institute, New Delhi. He has developed 25 Basmati rice varieties using molecular breeding tools to combine resistance to biotic and abiotic stresses. These varieties are grown over 2 million hectares earning forex worth US$ 5.9 billion annually, while bringing smiles on the faces of millions of Basmati farmers. He has published more than 200 research papers in journals of repute and written two books. He is a Fellow of INSA, NASI & NAAS and recipient of Rafi Ahmed Kidwai Award, Bharat Ratna Dr. C. Subramaniam Award and Nana Ji Deshmukh Interdisciplinary Team Award of Indian Council of Agricultural Research and Best Teacher Award Dr. B.P. Pal award of Indian Agricultural Research Institute. He has also received prestigious Vasvik Award, Omprakash Bhashin Award, Ramchandra Rao Memorial Award and Dr. Darshan Sing Brar Award from Dr. Gurdev Singh Khush Foundation.

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Prof. V.K. Baranwal is an eminent plant pathologist and currently serves as ICAR National Professor at the Indian Agricultural Research Institute, New Delhi. He has made significant contributions to teaching and advanced research in Plant Pathology, focusing on high-throughput sequencing (HTS)-based genomics, rapid diagnostics, and the management of economically important plant viruses in field and horticultural crops. He is a Fellow of the National Academy of Agricultural Sciences and the National Academy of Sciences, India. Prof. Baranwal currently serves as an Editor for the National Academy of Agricultural Sciences and the Journal of Virological Methods.

Dr. R.K. Jain

Dr. R.K. Jain, formerly Dean and Emeritus Scientist, Indian Agricultural Research Institute, New Delhi, has served the Indian Council of Agricultural Research, New Delhi for over four decades in various capacities. He has made tangible contributions in the area of molecular diagnosis and genomics of emerging and re-emerging plant viruses affecting field and horticultural crops. He is a Fellow and Editor of the National Academy of Agricultural Sciences. He is also a Fellow & former President, Indian Phytopathological Society and a Fellow and former Vice-President, Indian Virological Society. He is a recipient of the Department of Biotechnology Overseas Associateship and United Nations Development Program fellowship.

Contents

Preface

Indian agriculture has made significant progress since independence. A remarkable transformation from a food-insecure to a food-surplus nation is a global success story. However, contemporary agriculture faces many challenges, including climate change, resource depletion, and evolving consumer. At the same time, there are enormous opportunities arising from advancements in science and technology in the areas of precision farming, biotechnology, digital agriculture, and sustainable practices. It is imperative to overcome these challenges and seize the opportunities in the agricultural sector to fully realize its potential as a global leader in sustainable, climate-resilient, and competitive agriculture. The next twenty-two years, leading up to the centenary of India's independence in 2047, which is referred to as the *Amrit Kaal*, offer vast opportunities to reimagine and rejuvenate the agriculture sector through bold policy reforms, cutting-edge research, inclusive education, and a robust extension system.

This publication, " *Indian Agriculture by 2047: A Roadmap for Research, Education and Extension*," serves as a strategic guide for aligning and reshaping agricultural research, education, and extension priorities with the broader national vision of a self-reliant, resilient, technologically empowered, and developed India. It envisions a vibrant, inclusive, and innovative agricultural research, education, and extension ecosystem that empowers farmers, fosters resilience, explores global markets, and ensures rural prosperity. The publication draws upon the collective wisdom of domain experts, policymakers, researchers, and grassroots practitioners to outline a forward-looking, integrated framework that bridges knowledge and practice. The roadmap emphasizes the convergence of science and society, innovations in agri-tech, climate-resilient farming, skill-based education, and last-mile extension connectivity. Additionally, it highlights the importance of inter-disciplinary collaborations, farmer-centric approaches, youth engagement, digital infrastructure, and policy reforms in transforming agriculture and the food system.

Many experts from the Academy contributed to shaping this publication. I sincerely appreciate all the contributors for preparing a visionary and futuristic agenda for agricultural research, education, and extension. I am confident that this publication will inspire all stakeholders to revisit their future agenda to translate actions into impactful outcomes, paving the way forward during the *Amrit Kaal* for a developed India.

New Delhi

Himanshu Pathak
President

Acknowledgements

This publication, "*Indian Agriculture by 2047: A Roadmap for Research, Education and Extension*," has materialized due to the commendable contributions of various domain experts. We sincerely thank all the conveners and chapter authors for their willingness to contribute, organize interaction meetings with experts, collate information, and prepare visionary chapters. Their invaluable insights, expertise, and dedication have laid a vision and pathways for transforming agricultural research, education, and extension, ultimately making India a developed nation by 2047.

The genesis of this publication began with a Panel Discussion organized by the Academy on June 4, 2023. Several fellows of the academy and experts provided their valuable inputs during this discussion. Notable contributors included Dr. R.C. Agrawal, Dr. Suresh Babu, Dr. Pratap S. Birthal, Dr. Pitam Chandra, Dr. R.K. Jain, Dr. J. K. Jena, Dr. J.C. Katyal, Dr. Shaik N. Meera, Dr. R.T. Patil, Dr. Rajender Parsad, Dr. V. Prakash, Dr. E.V.S. Prakasa Rao, Dr. S. Rasheed, Dr. H.P. Singh, Dr. N.K. Singh, Dr. R.C. Srivastava, Dr. Taru Sharma, Dr. N.K. Tyagi, and Dr. B. Venkateswarlu. We extend our heartfelt thanks to all of them for their insightful contributions that have enhanced the quality of this publication.

We acknowledge the efforts of the Executive Director and the members of the NAAS Secretariat in bringing out this publication. Special thanks are extended to Ms. Rashmi Singh for her excellent editorial support.

We hope this publication serves as a valuable reference for science leaders, policymakers, researchers, students, donors, and other stakeholders in reshaping the future agenda of agricultural research, education, and extension, contributing to the goal of making India a developed nation by 2047.

New Delhi

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Abbreviations

ABC	Artificial Breeding Centres
ABNJ	Areas Beyond National Jurisdiction
ACs	Agricultural Cooperatives
ADB	Asian Development Bank
AHE	Agricultural Higher Education
AHSSOH	Animal Health System Support for One Health
AI	Artificial Intelligence
AICRP	All India Coordinated Research Project
AIEEA	All India Entrance Examination for Agriculture
AIGs	Agricultural Interest Groups
AKMU	Agri-Knowledge Management Unit
AMB	Agriculture Marketing Board
AMS	Agricultural Marketing System
AOP	Annual Operating Plan
APEDA	Agricultural and Processed Food Products Export Development Authority
APPI	Animal Pandemic Preparedness Initiative
AR	Augmented Reality
ARIS	Agricultural Research Information System
ARV	AI and Robotics Ventures
ARYA	Attracting Rural Youth in Agriculture
ASEAN	Association of Southeast Asian Nations
ASF	African Swine Fever
ASHOKA	Advanced Supercomputing Hub for Omics in Agriculture
ATARIs	Agricultural Technology Application Research Institutes
ATMA	Agricultural Technology Management Agency
AUs	Agricultural Universities
AWD	Alternate Wetting and Drying (Rice Cultivation)

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BAHS	Bachelor of Animal Husbandry Science
BAIF	Bharatiya Agro Industries Foundation
BAU	Business As Usual
BBF	Broad Bed Furrow (Farming Technique)
BBM1	BABY BOOM1
BCM	Billion Cubic Meters (Water)
BIMSTEC	Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation
Bio-MEMS	Biological Micro-Electro-Mechanical Systems
BLP	Blended Learning Platform
BPS	Biophysical Systems
BRL	Biotechnology Research Laboratory
BSMA	‘Broad Subject Matter in Agriculture
Bt	Billion Tonnes
CA	Conservation Agriculture
CAAST	Centers for Advanced Agricultural Science and Technology
CAGR	Compound Annual Growth Rate
CAUs	Central Agricultural Universities
CBG	Compressed Biogas
CBSE	Central Board of Secondary Education
CCCSHAU	Chaudhary Charan Singh Haryana Agricultural University
CCSAMMN	Climate Change and Sustainable Agriculture: Monitoring, Modeling, and Networking
CDM	Clean Development Mechanism
CDP	Community Development Program
CEA	Controlled Environment Agriculture
CF	Carbon Footprint
CHS	Cooperative Housing Societies
CIFE	Central Institute of Fisheries Education
CIGs	Common Interest Groups
CLRI	Central Leather Research Institute
COP	Conference of the Parties
COVID-19	Coronavirus Disease 2019
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats (Gene Editing)
CRV	Climate Resilient Varieties
CSCs	Common Service Centres
CSR	Corporate Social Responsibility
CUET	Common University Entrance Test

Contd...

DADF	Department of Animal Husbandry, Dairying & Fisheries
DAHDF	Department of Animal Husbandry, Dairying & Fisheries
DARE	Department of Agricultural Research and Education (India)
DATs	Disruptive Agricultural Technologies
DBT	Direct Benefit Transfer / Department of Biotechnology
DDGs	Deputy Director Generals
DDOs	District Development Officers
DIVA	Digital and Intelligent Value Chain for Agriculture
DNA	Deoxyribose Nucleic Acid
DoF	Department of Fisheries
DSR	Direct Seeding of Rice
DST	Department of Science and Technology
EAFM	Ecosystem Approach to Fisheries Management
EBP	Ethanol Blended Petrol
EDC	Entrepreneurship Development Cell
EEIs	Extension Education Institutes
EEZ	Exclusive Economic Zone
EPI	Expanded Program on Immunization
FAIR	Findable, Accessible, Interoperable, Reusable Principles
FAOs	Food and Agriculture Organizations
FAS	Foreign Agricultural Service
FFDAs	Fish Farmers Development Agencies
FFSLM	Farmer Field Schools on Land Management
FLD	Front Line Demonstration
FMD	Foot and Mouth Disease
FPCs	Farmer Producer Companies
FPOs	Farmer Producer Organizations
FSI	Forest Survey of India
FSSAI	Food Safety and Standards Authority of India
FTC	Farmers' Training Centre
GABA	Gamma-Aminobutyric Acid
GAP	Good Agricultural Practices
GBPUA&T	Govind Ballabh Pant University of Agriculture and Technology
GDP	Gross Domestic Product
GEC	General Education Council
GER	Gross Enrolment Ratio
GHG	Green House Gas

Contd...

GIS	Geographic Information System
GITA-RAS	Genetically Improved, Technology Augmented - Resilient & Responsible Aquaculture Systems
GoI	Government of India
GPAI	Global Partnership on Artificial Intelligence
GST	Goods and Services Tax
GVA	Gross Value Added
GWAS	Genome-Wide Association Study
GWCF	Groundwater Conservation Fee
GWP	Global Warming Potential
GYAI	Global Youth Agriculture Initiative
HAE	Higher Agricultural Education
HECI	Higher Education Commission of India
HIG	High-Income Growth
HMP	Holistic Management Practices
HRD	Human Resource Development
HYVs	High Yielding Varieties
HYVs	High Yielding Varieties
IAAP	Intensive Agricultural Area Program
IARI	Indian Agricultural Research Institute
IASRI	Indian Agricultural Statistics Research Institute
ICAR	Indian Council of Agricultural Research
ICDS	Integrated Child Development Services
ICRA	Indian Council of Rural Affairs
ICT	Information and Communication Technology
IFAD	International Fund for Agricultural Development
IFFCO	Indian Farmers Fertiliser Cooperative Limited
IFS	Integrated Farming System
IGFRI	Indian Grassland and Fodder Research Institute
IIHR	Indian Institute of Horticultural Research
IIPR	Indian Institute of Pulses Research
IIRR	Indian Institute of Rice Research
IMTA	Integrated Multi-Trophic Aquaculture
INDC	Intended Nationally Determined Contribution
INM	Integrated Nutrient Management
IoT	Internet of Things
IPC	Integrated Pest Control
IPCC	Intergovernmental Panel on Climate Change

Contd...

IPM	Integrated Pest Management
IPM INM	Integrated Pest Management & Integrated Nutrient Management
IPPU	Industrial Processes and Product Use (GHG Emissions)
IPU	Inter-Parliamentary Union
IRRI	International Rice Research Institute
ISM	Indigenous Soil Management
ISRO	Indian Space Research Organisation
ITC	Indian Tobacco Company / International Trade Centre
IUU	Illegal, Unreported, and Unregulated (Fishing)
IVF ETT	In Vitro Fertilization and Embryo Transfer Technology
IVRI	Indian Veterinary Research Institute
IWRM	Integrated Water Resource Management
JRF	Junior Research Fellowship
KCC-CHAKSHU	Kisan Call Centre-Collated Historically Aggregated Knowledge-based System with Hypertext User-interface
KCCs	Kisan Credit Cards
KPIs	Key Performance Indicators
KTI	Kunitz Trypsin Inhibitor
KVK	Krishi Vigyan Kendra
LCA	Life Cycle Assessment
LDN	Land Degradation Neutrality
LEDs	Light Emitting Diodes
LHDCP	Livestock Health & Disease Control Program
LLP	Limited Liability Partnership
MA&FW	Ministry of Agriculture & Farmers Welfare
MACE	Mainstreaming Agricultural Curriculum in School Education
MANAGE	National Institute of Agricultural Extension Management
MAS	Marker-Assisted Selection
MCI	Medical Council of India
MCS	Monitoring, Control, and Surveillance Systems
MD	Managing Director
MES	Management Information System
MFAH&D	Ministry of Fisheries, Animal Husbandry & Dairying
MGNREGA	Mahatma Gandhi National Rural Employment Guarantee Act
Mha	Million Hectares
MHA	Ministry of Home Affairs

Contd...

MI	Micro-Irrigation
ML	Machine Learning
MoA&FW	Ministry of Agriculture & Farmers Welfare
MoEFCC	Ministry of Environment, Forest and Climate Change
MOET	Multiple Ovulation and Embryo Transfer
MoU	Memorandum of Understanding
MP	Member of Parliament
MPCs	Milk Producer Companies
MSP	Minimum Support Price
Mt	Million Tonnes
MWRRD&GR	Ministry of Water Resources, River Development & Ganga Rejuvenation
NAARM	National Academy of Agricultural Research Management
NAAS	National Academy of Agricultural Sciences
NABARD	National Bank for Agriculture and Rural Development
NABI	National Agri-Food Biotechnology Institute
NAC	National Advisory Council
NADP	National Agricultural Development Program
NAEAB	National Agricultural Education Accreditation Board
NAEP	National Agricultural Extension Policy
NAHEP	National Agricultural Higher Education Project
NAPCC	National Action Plan on Climate Change
NAREES	National Agriculture Research, Education, and Extension System
NARI	National Agricultural Research Institute
NATP	National Agricultural Technology Project
NBM	National Bamboo Mission
NCERT	National Council of Educational Research and Training
NCU	National Carbon Units
NDC	Nationally Determined Contribution
NDDB	National Dairy Development Board
NDRI	National Dairy Research Institute
NEP	National Education Policy
NePPA	National *e*-Governance Plan in Agriculture
NESA	National E-Governance Services in Agriculture
NFDB	National Fisheries Development Board
NFSM	National Food Security Mission
NGOs	Non-Governmental Organizations
NHERC	National Higher Education Regulatory Council

Contd...

NIANP	National Institute of Animal Nutrition and Physiology
NIAP	National Institute of Agricultural Economics and Policy Research
NICRA	National Initiative on Climate Resilient Agriculture
NIPGR	National Institute of Plant Genome Research
NIRF	National Institutional Ranking Framework
NLP	Natural Language Processing
NMAET	National Mission on Agricultural Extension and Technology
NMSA	National Mission for Sustainable Agriculture
NNAJ	National Network of Agri-Journalists
NRM	Natural Resource Management
NSA	National Seed Association
NZC	Net Zero Carbon
NZCC	Net Zero Carbon Commitment
ODOP	One District One Product
OMIC	Omics Technologies
PAU	Punjab Agricultural University
PCR	Polymerase Chain Reaction
PGS	Participatory Guarantee System
PMFBY	Pradhan Mantri Fasal Bima Yojana
PMKSY	Pradhan Mantri Krishi Sinchayee Yojana
PM-PKY	Pradhan Mantri Prakritik Krishi Yojana
PM-PRANAM	Promotion of Alternate Nutrients for Agriculture Management
PoC	Point of Care
PPE	Personal Protective Equipment
PPPs	Public-Private Partnerships
PRI	Panchayati Raj Institutions
PRIs	Panchayati Raj Institutions
PSSB	Professional Standard Setting Body
QSAR	Quantitative Structure-Activity Relationship
QTL	Quantitative Trait Locus
R&D	Research and Development
RAES	Resilient Agricultural Education System
RAFTAR	Remunerative Approaches For Agriculture and Allied Sectors Rejuvenation
RAWE	Rural Agricultural Work Experience
RCP	Representative Concentration Pathway
READY	Rural Entrepreneurship Awareness Development Yojana

Contd...

RKVY	Rashtriya Krishi Vikas Yojana
RNGs	Renewable Natural Gas
SAARC	South Asian Association for Regional Cooperation
SAMETIs	State Agricultural Management and Extension Training Institutes
SAPCC	State Action Plan on Climate Change
SAUs	State Agricultural Universities
SCM	Supply Chain Management
SDGs	Sustainable Development Goals
SDN	Sustainable Development Network
SEDGs	Socially and Educationally Disadvantaged Groups
SHC	Soil Health Card
SHGs	Self-Help Groups
SIDP	Stabilization and Inclusive Development Programme
SMART	Specific, Measurable, Achievable, Relevant, Time-bound
SMFDA	Small and Marginal Farmers Development Agency
SOC	Soil Organic Carbon
SRF	Senior Research Fellowship
Super SMS	Super Straw Management System (for Crop Residue)
TAAS	Trust for Advancement of Agricultural Sciences
TNAU	Tamil Nadu Agricultural University
TVC-4-SNAP	Technology-Mediated Value Chain for Safe and Nutritious Aquatic Food/Fish Products
UAV	Unmanned Aerial Vehicle (Drones)
UGC	University Grants Commission
UIP	Universal Immunization Program
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
UV	Ultraviolet
VAT	Value Added Tax
VCM	Voluntary Carbon Market
VCRMC	Village Climate Risk Management Committee
VR	Virtual Reality
WEF	Water Energy Food
WEFE	Water-Energy-Food-Ecosystem Nexus
WF	Water Footprint
WHO	World Health Organization
WMP	Watershed Management Program

1

Indian Agriculture: Vision 2047[1]

P.K. Joshi[2]

1. Introduction

Indian agriculture has exhibited extraordinary progress since independence in 1947. There has been a giant leap in the production of food grains; it went up from a very low level of 50.82 million tons (Mt) in 1950-51 to an all-time high of 332.22 Mt in 2023-24. Similarly, the rice production reached 137.82 Mt in 2023-24 from a mere 20.58 Mt in 1950-51. The corresponding increase in wheat production has been from 6.46 Mt to 113.29 Mt. Such an amazing transformation has become a global success story to emulate by many developing countries. Indian agriculture has proved wrong all global projections of famine and starvation, which predicted huge food shortages to meet its growing population. The success was not only confined to food grains but also to all food commodities. For example, the milk production increased from 20 Mt in 1965-66 to 239.30 Mt in 2023-24, and fish production increased from 1.37 Mt to 18.40 Mt. Similarly, horticulture production has risen to 353.19 Mt in 2023-24 from 96 Mt in 1990-91. India used to be a deficit country in most of the food commodities at the time of independence but has now emerged as one of the leaders in agricultural exports. The export of agricultural commodities has reached Rs. 4088 billion (11% of total national export), and the net trade surplus has been Rs. 1360 billion in 2023-24.

The agricultural research, education, and extension system has significantly contributed to the transformation of Indian agriculture. The system has rapidly grown over the years and has become one of the largest systems

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1 This chapter is compiled and prepared based on the Panel Discussion organized by the NAAS on 4th June 2023. Most of the information shared in the chapter is based on the inputs received from the panel members including Dr. R.C. Agrawal, Dr. Suresh Babu, Dr. Pratap S. Birthal, Dr. Pitam Chandra, Dr. R.K. Jain, Dr. J. K. Jena, Dr. J.C. Katyal, Dr. Shaik N. Meera, Dr. R.T. Patil, Dr. Rajender Parsad, Dr. V. Prakash, Dr. E.V.S. Prakasa Rao, Dr. S. Rasheed, Dr. H.P. Singh, Dr. N.K. Singh, Dr. R.C. Srivastava, Dr. Taru Sharma, Dr. N.K. Tyagi, and Dr. B. Venkateswarlu. Their contribution in the chapter is duly acknowledged.

2 National Academy of Agricultural Sciences, New Delhi.

in the world. The first agricultural research institute was the Imperial (now Indian) Agricultural Research Institute (IARI), established in 1905 at Samastipur, Pusa, Bihar. In 1929, the Imperial (now Indian) Council of Agricultural Research (ICAR) was established as the first step towards institutionalizing agricultural research and extension in India. The first agricultural university, the Uttar Pradesh Agricultural University (now GB Pant University of Agriculture and Technology), was established in 1960 at Pantnagar. There are 113 research institutes under the Indian Council of Agricultural Research and 74 agricultural universities, which are spread across the country. Similarly, the agricultural extension system has expanded over time and launched different approaches and methods to disseminate improved agricultural technologies. It started with the launch of the Community Development Program (CDP) in 1952 as a holistic approach to rural development that included agriculture as one of the components. Over the years, ICAR has evolved an effective and well-tested front-line extension system at the grassroots level, which is exemplary and admired worldwide. In 1974, a new program, “Krishi Vigyan Kendra” (KVK), was launched in Puducherry (formerly Pondicherry). Presently, there is a network of 731 KVKs spread across the country, with at least one located in almost every district of India (NAAS. 2022).

As stated earlier, the last 75 years of Indian agriculture have witnessed an exceptional trajectory. In the next 22 years, when India celebrates 100 years of its independence in 2047, it will likely face several new challenges and offer enormous opportunities. Hon’ble Prime Minister has envisioned India to be a developed country when it completes 100 years of independence. It emerges as the third largest economy in the world, only next to the United States of America and China. The next 22 years, from now till 2047, the Hon’ble Prime Minister has named the period as *Amrit Kaal*.

To meet the desired goals, the agriculture sector, which has about a 15% share in the gross domestic product, will play a key role. Therefore, there is a need to identify future research thrust areas along with pro-agriculture policies, which would overcome new challenges and harness emerging opportunities. This document attempts to explore high-priority areas and prepare a roadmap for agricultural research, education and extension during the *Amrit Kaal*. The chapter is divided into five sections. After providing the context, the second section presents the agricultural sector’s global and domestic challenges and opportunities during the next 22 years. The third section provides Vision, Mission, and high priority research, education, and extension areas, followed by a roadmap for the *Amrit Kaal*. The fifth section is an epilogue, which presents conditions for successfully achieving the roadmap.

2. Challenges and Opportunities

2.1. Global challenges and opportunities

A mammoth global population of 9.6 billion in 2047, about 2 billion more than in 2021 (7.8 billion), would need more food to be produced from shrinking land and other natural resources. There are projections that there would be a whopping 10% rise in migration from rural areas to cities, and the result would be that 67% of the global population will live in urban areas (Worldometer, 2024). Unfortunately, the size of land holdings is declining due to competition for land by other sectors. There are about 570 million small and marginal farmers (<2 ha), whose number is expected to rise further. It is anticipated that the current ways of increasing food production may not meet future demands due to shrinking land, degradation of natural resources and climate change. The excessive and injudicious use of man-made chemicals degrades the health of natural resources and adversely influences human and animal well-being. These also generate unsustainable levels of greenhouse gases and an unacceptable volume of pollutants and contaminants. Globally, these will dramatically influence agricultural production; developing countries, the poor and vulnerable class, will suffer the most. Some of the major consequences of such a scenario are listed below:

- About 50% more food would be needed due to the diminishing share of agricultural land area/capita (from 0.61 ha in 2018 to 0.49 ha in 2047); there are fewer chances of any significant decrease in the number of undernourished (957 million) and malnourished (~700 million) people.
- Greater pressure on natural resources - hitting hard the land quality and target food grain productivity growth rates that have already fallen from peak values of about 3 to 1.5%.
- Without sustainable intensification processes, the degradation of soil, water, and biodiversity will magnify and intensify the loss of agricultural resilience.
- In the absence of appropriate measures, the global warming and climate change uncertainties will be less predictable and further influence agricultural production.
- Growing income and unfolding globalization are leading to increasing demand for non-cereals and nutritious foods (such as pulses, fruits, vegetables, animal products), with a yearning for affordable, safe, and nutritious foods.

- Waning interest in farming, particularly of small-scale farmers who will be the first to seek employment outside agriculture and migrate to cities; depleted young and able-bodied workforce will leave behind women and old people to manage agriculture; mounting need for innovative but labor-less solutions and area-specific precise solutions backstopped by information and communication technology, robotics, and machines.

Global opportunities are also rapidly expanding in agriculture due to technological advancements, shifting consumers' taste & preferences, and the growing demand for sustainable food production. Innovations such as biotechnology, precision agriculture, and climate-resilient varieties, and the emergence of high-value & processed commodities are transforming traditional farming practices, enhancing yields, and reducing environmental impact. Additionally, the rise of agri-business and digital agriculture is opening new markets and investment avenues, particularly in developing countries with untapped potential. Agriculture is also expected to offer entrepreneurs, investors, and researchers enormous potential to drive food security, economic development, and environmental sustainability.

The future direction of global agricultural R&D should respond to the scenario presented above. New innovative R&D solutions should be inclusive, efficient, sustainable, and resilient.

2.2. National challenges and opportunities

The scenario that has been discussed for world agriculture will not be different for India during the *Amrit Kaal*. To become a developed nation by 2047, the economic growth should be about 8% per year from the existing rate of about 6.4%. The role of agriculture will be crucial in significantly contributing to achieving higher economic growth. However, indications show that Indian agriculture will face more intense future challenges. India's 2047 population will peak at 1.61 billion (The Hindu 2020, July 16). leaving only 0.11 ha of agricultural land to feed every individual per annum (versus the global figure of 0.5 ha/per capita of agricultural land). Water availability for agriculture, which is declining in quantity and quality, will deteriorate further. These will further contribute to a deepening crisis for producing enough food and nutrition (about 1 out of 4 people are hungry and malnourished globally) in the face of mounting stresses on the health of natural resources (land, water, and biodiversity). Falling quality and quantity of natural resources will promote a rise in temperatures/climate change, directly and indirectly responsible for a loss in the production of all food commodities. Estimates are that the productivity of a crucial cereal like wheat in India will decline by up to 6 Mt if the atmosphere becomes warmer by 1 °C (ICAR, 2015).

Over-dependence on chemical fertilizers instead of reviving productivity by use of native sources will worsen the productivity scenario further, both due to deteriorating soil health, increasing greenhouse gas emissions, and rising temperature. If holistic strategies are not in place to improve input use efficiency, build up crop adaptability, and up-scale resilience to climate change, the production efficiency will fall beyond the threshold for its revival. Persisting with the wrong policy of subsidizing chemical inputs and energy, adoption of wrong practices (such as tillage, monoculture, and cereal-cereal rotation) will be another blow to the sustainable growth in agricultural production. With falling productivity growth and diminishing farm income, many farmers will be ready to quit agriculture as a profession. Though this is desirable, there should be enough employment opportunities outside the agriculture sector.

A fall in agricultural production will cause less availability/capita, poor affordability/household, and limited market accessibility, further adversely affecting food insecurity. Additionally, by 2047, if not more, an equal proportion of the population will be distributed between rural and urban areas. This will leave agriculture to be managed by women and relatively older people who will be less inclined to accept knowledge-intensive agricultural practices. Until agricultural departments and educational institutions regularly interact with farmers through various government programs and initiatives, and help them earn more income, the current tendency of farmers to leave agriculture and the waning interest of youth in the agriculture business will amplify further. Without improving investment in R&D, the generation of future-relevant technologies will be at stake.

With the above agricultural scenario for India on the global canvas, the demand for food commodities will rise to newer levels. The estimates of NITI Aayog (NITI Aayog. 2023) show that the demand for foodgrains in 2047-48 will be 402 Mt under the business-as-usual scenario and 415-437 Mt under the high-income scenario. The demand for vegetables will be 365 Mt and 385-417 Mt, respectively. Demand for milk will also rise to 480 Mt under business-as-usual and 527-606 Mt under high-income scenario.

Enough opportunities exist during the *Amrit Kaal* for the transformation and growth of the agricultural sector. Integrating advanced technologies like drones, AI, and precision agriculture can significantly boost agricultural productivity, efficiency, and sustainability. The rise of agri-tech start-ups is revolutionizing supply chains and market access, while growing global demand opens new avenues for exports of organic and ethnic produce. Government initiatives such as promoting farmer producer organizations (FPOs), cooperatives, digital agriculture, and financial schemes also provide a strong foundation for agri-business. In addition, the focus is on sustainable practices, and youth-driven agri-entrepreneurship can ensure a resilient and future-ready agricultural sector.

To overcome the challenges and harness opportunities by 2047, the existing research, education, and extension solutions seem outdated. Therefore, there is a need to construct the future strategy for research, education and extension, and develop a demand-driven portfolio to overcome the challenges and make India a global leader in agriculture. Therefore, the goal, objectives, and direction of the global agricultural research, education, and extension should respond to the above-illustrated scenario. It will require new innovative solutions to help farmers sustainably improve productivity and income with reduced risk and cost of cultivation, less labor, and higher value of output. The following section presents vision, mission, and high-priority research, education, and extension areas during the *Amrit Kaal*.

3. Vision and Mission

Intensification and commercialization of food and agriculture systems during the last seven decades have remarkably increased the food supply and reduced poverty, but simultaneously created dramatic environmental consequences, accelerated climate change, biodiversity loss, land degradation, desiccation, and degradation of soil and water resources. While challenges are enormous, opportunities are also no less. The opportunities are an increase in demand for high-value and processed food commodities, integration of global value chains, emergence of new tools and techniques for farming, marketing, and value addition, and advent of precision and digital agriculture. Under such a scenario, rejuvenating health and further enhancing the carrying capacity of the available natural production system, particularly land, water, and atmosphere, without compromising the food security of the growing population, along with harnessing the opportunities, needs to be addressed during the *Amrit Kaal*.

Vision

By 2047, India aspires to become a *Vishwaguru* in agricultural science and innovation to attain sustainable food and nutritional security, improve the environment, and fulfill the zero-carbon emission commitment.

Mission

Transform the agricultural research, education, and extension system to improve efficiency and global competitiveness in high-tech sectors, digital power, and unicorn value to ensure food and nutrition security, economic prosperity with social inclusion, environmental sustainability, and zero carbon emissions.

To accomplish the vision and mission, the objectives of the agricultural research, education, and extension system should align with:

- Enhancing productivity through gene revolution, relieving pressure on natural resources, and the use of man-made sources (efficiency) to protect against threats to agricultural resilience from climate change-related abiotic (flooding, drought, thermal, etc.) and biotic (biodiversity loss, disease, and pest incidence, etc.) stresses. Need would be for vertically aligned but well-integrated food systems that generate employment and serve diverse consumer requirements.
- Minimizing the cost of cultivation by creating and infusing well-organized resource management tech innovations that inspire efficiency, reduce dependence on man-made inputs, reduce pre- and post-harvest losses, and improve labor productivity. Technology automation, remote sensing involving machines, artificial intelligence, and big data analytics would be needed to produce evidence-driven results.
- Nurturing the rise of low-volume, high-value agriculture, which typically suits the needs and aspirations of small and marginal farmers, by creating innovations in vertical farming to produce more from less space and energy.
- Generating high-quality, nutritious cultivars by genetic enhancement via exploitation of the power of genetic engineering.
- Advancing the development of feeds to contain livestock-related greenhouse gas emissions.
- Reducing the grain use burden of the poultry industry by innovating protein-rich alternatives as feed.
- Delivering research efficiently and effectively for farmers' prosperity, food security, and soil health with minimum climate change.

4. Priority areas

During the *Amrit Kaal*, there is a need to reorient research objectives covering food production systems and alternative strategies to intensify yield advantages by infusing steady improvements. Develop novel practices for improving soil and water health, reducing environmental impacts, and managing outbreaks of emerging pests and diseases of various food grains, animals, and horticultural crops. Current restrictions on the exploitation of biotechnology (genetically modified and genetically enhanced) to optimize productivity and to reduce the cost of cultivation are unnecessary and should be shelved henceforth. Countries allowing unrestricted use of genetically modified crops (e.g., soybean) have several times more productivity with less use of chemical inputs. India needs to emulate that in its research methodology and approach.

In the era of *Amrit Kaal*, the national agricultural research system needs to develop a few flagship programs to achieve the mission. Some of the priority areas are listed below:

4.1. Characterization of genetic stock

Genetic enhancement is the major option to bridge the demand and supply gap under normal situations and projected scenarios of growing frequency and intensity of stresses. India has a large pool of landraces and genetic material of different crops, animals, fish, and even microbes. For example, the total number of accessions for crops is about 466,491. There is a need to characterize these to explore the genes having traits of increasing yields, enhancing resource use efficiency, developing resistance against biotic and abiotic constraints, building resilience, improving quality & nutritional levels, and improving the shelf-life. There is an urgent need to conserve and utilize the landraces and wild relatives of the crop plants, as these are depleting rapidly due to developmental pressure. Furthermore, the modern high-yielding cultivars of most crop species have a narrow genetic base due to dual domestication and breeding bottlenecks. Thus, pre-breeding becomes a priority for infusing greater resilience broader genetic base in the new crop varieties. Landraces and wild relatives are a vast reservoir of useful new genes, which need to be discovered using functional genomics tools and high-throughput trait phenotyping. Also, there is a need to use new techniques such as genomics, transcriptomics, proteomics, metabolomics and ionomics, genomics-assisted selection, genetic engineering, genome editing, artificial intelligence, data mining, precision phenotyping, and nanotechnology.

In the livestock and fishery sectors (ICAR 2015), research can be utilized in the frontier areas like stem cells, pharmacokinetics and nutrigenomics, transgenic animals, proteome analysis, sirna technology, bio-sensor applications, targeted nano-delivery of drugs; IVF-ETT, etc., can be gainfully utilized for strengthening system efficiency. Some important issues for investigation are: livestock genetic improvement using phenomics, genomics and bioinformatics tools; breeding transgenic animals capable of producing tailor-made milk/meat to cater to the specific needs; understanding of the basis of genetic resistance in domestic species of livestock with DNA markers for disease-resistant genes and the ability to diagnose specific genotypic markers that correlate with susceptible and resistant phenotypes; regenerative medicine, micro- electro- mechanical systems (Bio-MEMS), pharmacy-on-chip, implanted body regulator, gene-based preventive medicine and bio- electronics; efficient nutrient delivery in animals through application of nano-technology; and development and strengthening of bio-safety capabilities. Cytogenetics and genotoxicity of fish and shellfish; extraction and characterization of bio-molecules having therapeutic and industrial significance; identification of biosynthetic gene clusters in aquatic bacteria to produce novel bioactive compounds are some other frontier areas for research.

Characterization should explore new genes for improved product quality to enhance features like looks, shelf-life, taste, flavor, culinary/processing value, nutrition, health, and consumer safety. Involvement of heirloom varieties/species of known product quality traits in breeding programs will be immediately relevant. Infusion of the latest developments in plant and animal breeding methods, like gene editing, offers various genetic enhancement possibilities for managing biotic and abiotic stresses and building product nutrition density. It is reiterated that the government of India should unshackle the use of biotechnology to generate cultivars that yield quality produce.

4.2. Harmonize Water-Food-Energy (WEF) nexus for managing competing demands and ensuring the integrity of the ecosystem

The WEF nexus approach proposes integration and interdependence across various sectors as a fundamental step for ensuring resource security in the context of resource scarcity and the climate change crisis in an increasing and competing demand for water, energy and food. The research framework of WEF nexus approach would require multi-centric and multi-scales, which treats different sectors as equally important. Globally, it is emerging as an instrument for development planning. It holds promise for Indian agriculture, where five transitions, namely, urbanization, nutrition, energy, agriculture, and climate, simultaneously impact the WEF security. The WEF Nexus approach will also directly address five Sustainable Development Goals 1 (zero poverty), 2 (no hunger), 6 (Clean water and sanitation), 7 (Renewable energy), 13 (Climate Action), but impacts all the 17 goals.

The research questions should be: (a) How can development needs (food, water, energy) be met in a sustainable manner without compromising ecosystem security? (b) Which individual innovations and their combination could translate into achieving the desired outputs? (c) What are the policy mixes that would give solutions that are economically viable, socially acceptable, and ecologically green? and (d) How it would contribute to decarbonising the Food and Agriculture System. The WEF applications are highly data-intensive. Digital technologies can enable the collection of accurate and real-time data on soil health, water availability, and climate conditions. This information can be used to develop targeted policies and interventions to promote productivity, resilience, and emissions management.

4.3. Bio-circular economy in agriculture for producing value-added products and reducing land, water, and air pollution

The circular bioeconomy includes waste streams from renewable bio-resources to be looped back for recycling or converting from matter to energy by innovative biological production processes. In such a type of economy, biological resources, including plants, animals, fish, micro-organisms and organic wastes, are transformed into feed, energy and biomaterials within the ecological food boundaries of the ecosystem. Circular bioeconomy aims at "closing the loop" to prevent expansive and unfettered extraction of biological resources and defines goals such as sustainability and environmental protection. In the circular bioeconomy system, one system's waste is the next system's input. This requires a system approach from the perspective of large value chains. The "zero-waste" policy of circular bioeconomy has fueled the development of waste biorefineries, microalgal biorefineries, and lignocellulosic biorefineries. Research and development in biotechnology for commercialization will help realize the successful transition to the circular bioeconomy.

There is enormous scope for promoting the concept of bio-circular economy to reduce environmental pollution and produce useful products to boost the agrarian economy. Some of the prospective areas include: (a) microalgae and macroalgae (seaweeds in other words)—bio-extractors of nitrogen, phosphorus, CO_2, and toxic heavy metals from wastewater sources for third-generation biofuels and good solutions to the food-fuel-fibre-feed impasse. It could be part of a blue bio-economy. (b) algae have other uses besides being energy sources—production of omega-3 fatty acids, natural food colorants, dyes, fertilizers, bioplastics, protein-rich fish feed for aquaculture, and pharmaceuticals. (c) Aquaponics refers to breeding fish and cultivating food plants (vegetables, for instance) in an integrated system. (d) dairy waste and molasses waste to produce biohydrogen and bio-plastics. (e) generating biomethane and biohydrogen by co-digesting food and vegetable wastes.

4.4. Towards a zero-carbon commitment

India has committed to cutting its net-zero emissions by 2070 at the 26th Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC). At present, India is the fourth biggest carbon emitter (2.6 billion tons (Bt) of carbon dioxide per year), after China (11.5 Bt), the United States of America (5.1 Bt), and the European Union (3.3 Bt). In India, agriculture contributes about 16% of total greenhouse gas (GHG) emissions, which come from enteric fermentation (livestock 54%), agricultural soils (fertilize use 19%), rice cultivation (18%), manure management (7%), and field burning and agricultural residues (2%) (Aggarwal *et al*., 2022). Among several measures, it was also committed that India will get 50% of its energy from renewable resources by 2030, and by the same year to reduce total projected carbon emissions by one billion tons.

Several technologies and institutional models are available to mitigate GHG emissions and adapt to climate change. To promote these technologies, strategies for extending incentives and designing sustainable and inclusive business models need to be developed. Future research should focus on livestock management with twin objectives of enhancing productivity and reducing GHG emissions. Similarly, future agronomic research should be to (i) develop new forms of fertilizers, and (ii) devise technologies that improve fertilizer use efficiency. These options should save fertilizer and reduce GHG emissions, without adversely affecting crop productivity. New ways for rice cultivation need to be explored and promoted. Alternatively, high-value agricultural diversification farming systems in low-yielding rice areas can be developed to enhance farmers' incomes and reduce GHG emissions. To attain India's commitment, it will be important to mandate every research program to reduce carbon emissions or improve carbon sequestration without compromising agricultural production. In addition, some institutional arrangements and policies, such as carbon trading, will incentivize farmers to reduce carbon emissions.

4.5. Climate resilient agriculture

Climate change is adversely affecting agricultural production and food security. The small and marginal farmers are more vulnerable to climate change. The frequency and intensity of climate change have increased over time. Indian agriculture is witnessing an increase in temperature, unseasonal rainfall, sudden rise and fall in temperature, frequent floods, droughts, cyclones, and other weather events. The impacts of climate change on crop yields indicate that yield losses may be up to 60% by the end of the century, depending on crop, location, and future climate scenario(Aggarwal *et al*., 2022). The action against climate change has been included as one of the Sustainable Development Goals (SDGs). The global community has pledged to take urgent measures to overcome climate change and its impacts. The SDG 13 (Climate Action), stresses the need for strengthening resilience and adaptive capacity to climate-related hazards and natural disasters.

Climate-smart agriculture is the scientific community's response to the menace of climate change. However, more research is needed to understand the climate change-related risk profiles of different crops in various agroclimatic regions and accordingly manage them through appropriate technological interventions. The technological interventions need to be supplemented by appropriate institutional arrangements and policies.

4.6. Alternatives to chemical fertilizers

Globally, the fertilizer prices have increased enormously due to a sharp surge in prices of key feedstocks, namely, natural gas and coal. Some of the supplying countries also imposed certain export restrictions, which further aggravated the rise in fertilizer prices. It is envisioned that the prices of fertilizer will continue to be high in the future. Despite rising prices and import bills of fertilizers, the Indian government is not passing the burden to the farmers. In 2022-23, the budget allocated for fertilizer subsidy was as high as Rs. 2252 billion. Besides high subsidies on fertilizers, the excessive and injudicious use of chemical fertilizers adversely affects soil health and deteriorates water quality.

In India, fertilizer accounts for 30 to 40% of the total cost of crop production. It also contributes about 19% of GHG emissions in total emissions from the agriculture sector. Therefore, there is an urgent need to reduce fertilizer consumption without compromising agricultural production. To save fertilizer, future research may be (a) to produce more from less fertilizer, and (b) to find alternative sources of nutrients. Precision agriculture and protected agriculture will help in reducing fertilizer use. This will require identification of crop- and location-specific approaches on quantity, intensity, and timings of fertilizer application. To explore alternative sources of nutrients, a mega program may be initiated by involving research organizations, the private sector, and progressive farmers. Alternative sources may be local agricultural waste, by-products, animal dung, etc. It will require blending traditional wisdom with modern science to save inorganic fertilizers without adversely affecting agricultural production.

4.7. Enhance resource use efficiency

Global trade is unfolding. Therefore, there is a need to become competitive in agriculture to promote exports and check imports. Unfortunately, the cost of inputs (namely seed, irrigation water, fertilizer, pesticides, machines, labor, etc.) is continuously rising and adversely affecting the competitiveness of Indian agriculture. Further, rising input costs and declining response are responsible for a fall in production and an increase in overall costs. Rising input costs are also one of the reasons for increasing food inflation in the domestic market. To overcome such a situation, there is a need to enhance resource use efficiency to increase production and reduce the unit cost of production. Cutting down the use of inputs will reduce the production cost and improve the sustainability of soil and water resources. Fortification of low-value indigenous resources (organic sources and mineral resources) by high-value man-made interventions will cut the use of harmful chemicals, conserve foreign exchange, maintain productivity, improve product quality, and contain climate change.

There should be system-wide orientation by integrating biophysical characteristics and social capabilities. There is a need to introduce new designs of conservation agriculture, precision agriculture, protected agriculture, vertical farming, hydroponics, etc., which require low construction, running, and maintenance costs. In addition, mainstreaming the use of drones, soil sensors, and the Internet of Things will become necessary to provide system-wide methods to enhance precision/efficiency and reduce the cost of bought inputs, labor, and energy. Therefore, the research should focus on developing system-based sustainable approaches to environment-friendly agriculture, which explore resource management strategies and their roles in soil health improvement. Increasing crop yields to at least the global average is important. The increase in crop yields should be cost-effective, sustainable, and environmentally friendly.

Since soil quality is deteriorating, there is a need to exploit the microbiome science to scale up climate resilience across food systems. Develop research to exploit to the fullest the potential of soil microbiome for regenerating soil health, building resilience to adverse pollutants/contaminants, and producing nutritious and safe foods. Likewise, harness the gut microbiome of ruminants for maximizing feed efficiency and minimizing methane production, favoring climate change management.

4.8. Management of degraded lands

In India, an estimated 121 million ha (Mha) of land is degraded due to water and wind erosion, chemical and physical degradation, soil salinity/ alkalinity, and waterlogging. In the 14th Conference of the Parties (COP 14) of the United Nations Convention to Combat Desertification (UNCCD) in 2019, the Prime Minister of India committed to restoring 26 Mha of degraded lands and fulfilling the requirements of Land Degradation Neutrality (LDN). Given the future carrying capacity of land resources, it is important to increase productivity sustainably by introducing improved land management practices. The goal should be to (a) conserve and improve the health and quality of existing land; (b) reclaim the lost degraded lands; and (c) sustain the quality of land already reclaimed. (NAAS, 2022)

The National Academy of Agricultural Sciences prepared a roadmap to rehabilitate 26 Mha of degraded lands (NAAS, 2022). Some of the action points listed in the roadmap are: (a) develop national land use plan based on scientific evidence to restore, recover and regenerate degraded lands; (b) introduce location-specific precision agronomic practices such as conservation agriculture and regenerative agriculture; (c) introduce legislature to save ecologically productive lands from diversion to other uses; (d) introduce site-specific agro-forestry systems as per land capability classification; (e) develop location-specific Holistic Management Practices (HMP) to enhance soil organic carbon in the normal and degraded lands; and (f) tune agricultural extension system to educate farmers on reclaiming degraded lands through 'Farmer Field Schools on Land Management (FFSLM).

4.9. Productivity enhancement through mechanization, precision agriculture, and automation

Farm mechanization includes machines used in tillage, harvesting, thrashing, irrigation, processing, dairy appliances, oil processing, cotton ginning, rice hulling, etc. The main objectives of farm mechanization were to enhance overall productivity, save labor, and automate field operations to lower production costs through improved and timeliness operations with improved precision in the application of inputs, production of high-quality and value-added products, and energy.

The last decade has undergone a data-driven evolution in agriculture and allied sectors. The evolving field of disruptive technologies has recently made significant strides. The disruptive technologies have a critical role in developing breakthroughs in precise agricultural processes, data analytics and Artificial Intelligence (AI) techniques. The current definition of Agricultural Technology (AgriTech) is strongly associated with AI applications, indicating the progression from farming to smart farming. The Information and Data Evolution and AI techniques exploit multi-source data and sensors on farm equipment and plants in this newly evolving farming model.

The new era of farm mechanization is characterized by the emergence of sensor-based technologies, Robotics, Drones, and Automated tractors, which would enormously improve the efficiency and reduce the drudgery in agriculture (Box 1). These are categorized as self-driving farm machinery equipment that delivers farming duties even in the absence of farmers. These can be fully or partially autonomous and can be monitored remotely by a farmer. The benefits of next-generation mechanization are (a) increase productivity, (b) improve accuracy and consistency, (c) reduce labor cost, (d) ensure safety, and (e) improve sustainability. Below are some of the future research areas during the *Amrit Kaal*.

4.10. 3-D ocean farming

It is a regenerative farming technique for aquaculture to create 'blue carbon'. It uses the entire water column to grow restorative species. The focus is to develop polyculture practices for farming shellfish and high-value fast-growing seaweeds and kelps. These practices include using many water column layers, emulating high-activity water ecosystems like reefs, to increase productivity and biomass. These are considered the 'farms of the future' because they are low impact, no input (no freshwater, no feed, no fertilizer) and high yield, producing highly nutritious seaweeds without using any arable land (Agritecture, 2018). In addition, such farms act as effective carbon sinks (via kelp forests) and fight ocean acidification via shellfish + kelp forests that together filter nitrogen and phosphorus from the ocean using naturally occurring ocean currents.

India has enormous potential for 3D Ocean Farming because it has a large coastline (about 7,516.6 km), bordering the mainland and the islands with the Bay of Bengal in the East, the Indian Ocean on the South, and the Arabian Sea on the West. Currently, China and Indonesia have 80% market share of seaweed. The potential of 3D Ocean Farming needs to be harnessed to enhance the incomes of aquaculture farmers, improve their livelihood, and enhance the scope of the carbon sink.

Box 1. Future research areas in farm management.

Area of research	Future research considerations
Farm management cycle and operation	◆ How virtual and augmented reality would enhance the application of precision agriculture? ◆ How can smart indoor vertical farming evolve and support farming production? ◆ How can future AgriTech innovations reshape the farming processes? ◆ How to effectively develop and operationalize the autonomous farming tractors for various farm operations?
Sensor technology	◆ How can IoT-enabled platforms improve farming production for the sustainability of AgriFood sector? ◆ How can IoT-enabled regenerative agriculture to evolve the next decade? ◆ What are the required data sharing policies to ensure privacy and competitive advantage for the operations of each farm?
Robotics	◆ What are the next AI and Robotics Ventures (ARV) for socially and environmentally responsible farming? ◆ What is the role of AgriTech robots in the new agricultural operations? ◆ How can 3D mapping and monitoring contribute to the sustainability goals of each farm? ◆ How can hybrid (aerial-ground) drones improve operation management in an unmanned way for agricultural monitoring? ◆ How can drones be used for remote agricultural operations in crisis situations? ◆ How can hybrid drones and manned aviators collaborate for precision agriculture?

Source: *Konstantina Spanaki, Uthayasankar Sivarajah, Masoud Fakhimi, Stella Despoudi and Zahir Irani, 2022. Disruptive technologies in agricultural operations: A systematic review of AI-driven Agri-tech research. Annals of Operations Research, Springer, vol. 308(1), pages 491-524, January.*

4.11. Livestock, veterinary, and animal husbandry

The following areas need due attention in future agriculture during the *Amrit Kaal*:

4.11.1. Conservation and use of sex semen

Shortage of good semen doses, which has resulted in about 10% of the total breedable and calvable milch animals not being calved even once in their life. As such, to maximize the use of available limited germplasm, the promising reproductive biotechniques like multiple ovulation and embryo transfer (MOET) and ovum pick-up and in vitro fertilization should be utilized to the maximum extent, at least for breeding bull production. MOET, sexed semen, and sexed embryos of exotic germplasm also need to be used for faster multiplication of superior animals with high genetic potential, either crossbred or non-descript indigenous cattle.

4.11.2. Control and manage diseases

Diseases like and udder infection cause annual losses of at least Rs 20,000 and 6,053 crores, respectively. By controlling FMD, milk production can be increased by at least 5% annually, and meat export can be enhanced by 3-5 times. However, there is a big gap between demand and availability of different vaccines to control them, as against the demand of about >1000 million doses of FMD vaccines, total doses produced in India are not more than 400 million. Therefore, a strong Research and development program is needed to produce the required quantity of vaccines against common diseases of cattle, buffalo, sheep, goats, pigs, horses and poultry. The PPP mode could offer great opportunities in Research and development and in planning and implementing livestock disease control programs. They can also be active partners in developing a comprehensive package about disease awareness, epidemiology, surveillance, management and control measures for knowledge empowerment of farmers.

4.11.3. Animal feed and fodder

The demand for dry fodder, green fodder and concentrate was about 468, 213 and 81 tons (on dry matter basis), respectively, in 2020, whereas the availability was estimated to be 417, 138, and 44 Mt, respectively. It is important that a quality forage seed production chain is maintained, a five-year rolling plan is prepared, and the role of the private sector, as in other seed sectors, is encouraged. Further, the research on rumen microbiota, bioavailability of micronutrients, and alternate sources of feed and fodder is to be prioritized.

4.12. Disruptive Agricultural Technologies (DATs)

The future of agriculture is envisioned as more digital innovations that empower small farmers to adopt digital and non-digital innovations. These will enable them to overcome their present and future visible and hidden constraints for enhancing resource use efficiency, nutritional content, and climate resilience. This would require more automation and customized real-time solutions for various farm operations and business processes to enable end-to-end solutions and develop efficient, inclusive, sustainable value chains. Some initial efforts are in the incipient stage for personalized production to nutrition, blockchain-enabled traceability, IOTs for value chains, big data analytics, etc. This would require a further R&D boost for accelerated use to transform agriculture. Below are some areas to develop customized solutions for different agro-ecologies:

- *Robotics and automation*: Robots provide a significant new technology in the food and agriculture system to harvest crops, identify weeds and implement weed control (e.g. mechanically remove weeds and/or employ microwave technology to kill weeds), spot the onset of plant diseases or pests and execute treatments; deliver fertilizer, pesticides, and herbicides at specific sites. In soils, it may be used for soil testing and determining water-use effectiveness, and robotic 'ducks' in rice fields to control weeds without pesticides.

- *Drones and Unmanned Aerial Vehicles (UAV):* It is relatively inexpensive and reasonably simple to operate. Drones can be equipped with sensors, cameras, and specialized hardware to perform many functions in agriculture. These operations may include (a) development of high-definition maps of fields that provide an ability to create prescriptive-defined application of sprays, fertilizer, pesticides, and herbicides, (b) counting the number of plants, fruits and flowers to forecast yields; (c) measurement of chlorophyll, crop biomass, and plant health, ground temperature, plant numbers, soil water content, when equipped with multispectral, hyperspectral and thermal cameras, and (d) supplement the pollination process as 'nanobees' (miniature drones) when normal bee pollinators are absent or insufficient.

- *Nanotechnology:* Nanoscale science and engineering offers the potential to significantly revolutionize agriculture and food system by: (a) "re-engineering" of crops, animals, microbes, and other living systems at the genetic and cellular level; (b) development of efficient, "smart" and self-replicating production technologies and inputs; (c) development of tools and systems for identification, tracking and monitoring; and (d) manufacture of new materials and modified crops, animals and food products.

- *3D-Printed Food:* The combination of robotics and software has entered the realm of food manufacturing in the form of 3D printing, which can create complex geometries, tailored textures, and nutritional contents. The 3D-printing process compresses the value chain to a highly local system made of inputs (ingredients), a single controlled process (the 3D printer), and a single output (the food product); and may lead to designer and specialized food products. The technology may be employed to use tissue engineering to create meat and other food alternatives.

Digital technologies range from mobile apps to digital identities for farmers, to renewable/energy efficiency applications for agriculture, to portable agriculture devices and bio-fortified foods. It helps to automate the key business processes along the value chain, provide access to services and markets, and deliver customized solutions to the intended beneficiaries. Some of the prospective areas of digital agricultural technologies for fostering agricultural production, productivity, market access, traceability, food safety, climate resilience, resource use efficiency, etc., are: (a) smart urban farming; (b) market intelligence; (c) crop advisories; (d) supply chain traceability; and (e) digital finance for agri-entrepreneurs. Digital technologies will facilitate the agricultural value-chains to reduce the costs of linking various actors of the agri-food system, both within India and across countries, by providing, processing, and analyzing an increasing amount of data faster. Overall, the digital agricultural technologies will be used to leverage technology as a pathway for agricultural transformation in India. The success of the digitized agriculture would be based on integration and connectivity of the following elements: (a) sensors including drones, robotics and artificial intelligence, to initiate data acquisition in the field; (b) connectivity with autonomous transfer of data from sensors (for example, Internet of Things in Agriculture or IoT) by wireless communication between digital devices, e.g. computers, tablets, and smartphones; (c) analytical devices with software capability (machine learning, artificial intelligence, and handling of 'big' data) for storage, analysis, synthesis, and reporting the results.

5. Road Map during *Amrit Kaal*

Agriculture, including agricultural research, education, and extension, is a state subject. Hence, without agreement with respective state governments, it is impossible to introduce any reforms, whether these focus on genetic engineering, scientific land use, land lease rules, markets, mainstream precision agriculture practices, and reforms in agricultural education and extension systems. The first step to strengthen agriculture, including agricultural research, education, and extension system, is to create a Center-State body like the GST Council of India. This is important to bring on board the necessary reforms' agenda in agriculture to (a) enhance budget for agricultural research, education and extension; (b) facilitate to develop state-of-art science and education infrastructure; (c) necessary reforms in agricultural research, education and extension; and (d) policy reforms to effectively implement changing structure of agricultural research, education and extension system. This section provides some of the needed reforms in agricultural research, education, and extension during *Amrit Kaal*.

5.1. Reforms in agricultural research

Agricultural research is vital in enhancing agriculture's innovation, competitiveness, and sustainability. The existing system is key in increasing agricultural production, ensuring food security, and reducing poverty. But its potential is not fully harnessed to make it more efficient and globally competitive due to a few deficiencies, which include inadequate funding, poor coordination between research institutions, and weak linkages with the private sector. It also lacks state-of-the-art science instrumentation and infrastructure. Therefore, the basic aim of reforming agricultural research should be to make it an efficient, demand-driven, and self-rejuvenating system to keep pace with the global research and development agenda. It should contribute towards solving next-generation challenges, ensuring future demand for food, improving nutritional security, conserving natural resources, and improving the environment, including zero carbon emission. Some of the suggested reforms to strengthen and modernize agricultural R&D for supporting sustainable development are listed below:

- Enlarge budgetary provisions for science and technology to infuse modernity, relevance, efficiency, and effectiveness. At present, the agricultural research system is starving for operational funds. The existing funds are too meagre for undertaking research to meet the future complex challenges. Besides raising the funding share of agriculture R&D, reforms are also necessary to inspire: (i) a greater share of private participation and investment, and (ii) scientific accountability for the money spent on R&D.

- Decentralizing the decision-making process at different levels of hierarchy will improve the system's efficiency and enhance accountability.

- Enhance the skills of human resources to keep pace with the advances in science tools, techniques and methodologies.

- Strengthen institutional mechanisms for priority setting, monitoring and evaluation. Outdated and irrelevant research programs need to be terminated.

- Foster partnerships among national and international organizations, universities, the private sector, civil society, and farmers. Ensure that research programs are multidisciplinary and multi-institutional with effective participation of basic sciences.

- The changing climate has put uncertain and unknown pressure on the sustainable growth of the sector. Incidence of natural adversaries like drought, flooding, pests/diseases are going to be more common in the wake of global warming/climate change. Experience confirms that to deal with these productivity-negating episodes, the use of genetic engineering seems necessary. A policy reform on using biotechnology to develop and utilize genetically modified crops/varieties with proper safeguards is allowed henceforth. This move will not only help deal with a formidable adversary like climate change but will also facilitate the development of productive and nutrition-dense foods to manage the rise of hunger and malnutrition.

- The government should inspire the use of science and technology-driven growth of agriculture rather than emphasizing increased use of inputs. Accordingly, reforms are necessary in the technology transfer system. The National Mission on Agricultural Extension and Technology may be reformed to educate and train farmers in the art and science of precise and efficient use of provisioned inputs instead of focusing just on the supply of inputs (seed/planting material/implements). Fusion of all shades of ICT with the conventional way of technology transfer and use will hasten the transformation towards science-driven agriculture.

- Farmers will become more willing to use science and technology if they get a remunerative price for their produce. Normally, the focus of farmers' unions is on minimum support prices (MSP), subsidies and doles rather than demanding competitive modern markets and other reforms in agricultural enterprises that infuse into the sector vibrancy, self-reliance and economic attractiveness. In fact, decoupling of crop price support by an income support program (reduction in cost of cultivation by use of technology in place of wasteful and imbalanced use of inputs). Market and agricultural trade management reforms should be in consonance with the States and stakeholders.

- If land ownership rests with farmers, farmers generally invest in enhancing the quality of land and water resources. In India, farming on leased land is on the rise, which happens on oral understanding and not on formally recorded agreements. Reforms in the Land Tenancy Act are necessary to minimize the fear of owners losing their land and inspire lessees to improve the leased land, with the ensuing possibility of longer tenancies.

- Currently pursued policy of pushing natural farming (organic farming) is good only for selected crops (fruits and vegetables) and areas (regions having high native soil organic carbon (SOC) or those having high availability of recyclable organic manures), and definitely not for food crops. To strengthen the productivity and profitability of selected crops, organic farming should use the power of modern advances in science and technology.

- For sustaining growth in food grain production without harm to land, water and environmental health, the policy push should be to produce safe and nutritious food (as prescribed by the international organizations such as World Health Organization, Food and Agriculture Organization) by mainstreaming integrated use of organic manures and efficient use of necessary agro-chemicals. Those farmer groups who opt for integrated nutrient and supply management and produce evidence by generating environmentally benign goods (safe produce) and services (SOC build-up) may be suitably rewarded for that.

5.2. Human resource development

India has adopted a path of science-led development in agriculture, which has paid high dividends. Human resources generated by the National Higher Agricultural Education System played the key role in that pursuit. However, adversaries challenging agriculture's sustainable growth require updated faculty to educate and train students in subjects of contemporary relevance, future applicability, and facilities supporting new research objectives. All agricultural research and extension reforms will start from improving the agricultural education system. Some specific recommendations on higher agricultural education (HAE) are as follows:

- Complete implementation of the National Education Policy (NEP) 2020 in all agricultural universities, including private colleges. To follow the policy, all agricultural universities need to be converted into multidisciplinary institutions offering holistic multidisciplinary education.

- Investing to create linkages between Indian and foreign universities on the lines established during the 1960s with the US Land Grant Universities for training and enrolment of faculty/students is seen as helping develop a new look of higher agricultural education. Jointly develop advanced courses and research programs. Start dual degree, integrated, and sandwich programs with national and international universities/organizations.

- Agricultural education is a state subject. Unlike general education, which is on the concurrent list, DARE/ICAR will be constrained to fully infuse the goals and aims of the National Education Policy. It is recommended that ICAR get statutory powers like those available to the Veterinary Council of India. Appropriate teaching and learning system reforms will be necessary to generate future-relevant human resources (teachers, students, and others).

- Re-engineering of HAE to measure up to emerging concerns of sustainable development (ensuring the production of food, wood, and fibres while respecting the ecological, economic and social limits that guarantee the durability of that production) and attracting youth in agriculture; special emphasis on cost- and energy-efficient intensive land use techniques like vertical farming and post-harvest management.

- A comprehensive teaching and learning course on resource conservation technologies to build soil health, save water and preserve biodiversity for ensuring food security, containing climate change; the contents should harmonize theory and practice of natural farming in consonance with man-made inputs without any cost to sustainable food and nutritional security of a total food production system with no rise of adverse outputs (contaminants, pollutants, and global warming).

- Course context (knowledge and skills) and delivery (pedagogy) emphasize learning in dealing with varied aspects of a food production system, including management of agri-value chains; training in re-designing farmer-managed integrated farming systems and building skill and capability in entrepreneurship in sunshine agriculture. There is a need to phase out some of the traditional disciplines and introduce new degree programs in demand-driven disciplines aligned with career and job opportunities, such as Artificial Intelligence, Computational genomics, Nanotechnology, etc.

- Strengthen education covering theory and practice in novel subject domains like digital innovations using geo-tagging, satellite data, and drone technology to verify data on crop production (crop-cutting experiments) and improve intelligence on the insured area. Specific infusion of education and training for mainstreaming the use of drones, soil sensors, and the Internet of Things is necessary to provide system-wide solutions to enhance precision/efficiency and reduce the cost of bought inputs, labor, and energy.
- Launch a teaching learning course on environmental education to create awareness and sensitivity to environmental concerns, including knowledge and understanding of natural resources, to create an attitude of refraining from damaging their quality, and an inspirational motivation to maintain environmental health. Beginning school education, components of environmental education should also include elements of non-formal education to develop well-informed professionals and environment-literate public and farmers as an answer to deal with degrading natural resources and a threatened climate.
- In view of ongoing climate change and resilience loss in farming enterprises, creating risk-proofing infrastructure (financial instruments, capable human resources, soil and water conservation land configurations, and efficient) would be crucial.
- Develop revenue generation models for all the agricultural universities to become financially independent.

5.3. Reorient the agricultural extension system

The agri-food system transformation during the *Amrit Kaal* will be possible when the extension system embraces a series of paradigm shifts from incremental approaches to disruptive approaches. Existing Krishi Vigyan Kendras (KVKs) in more modern forms will enable rapid dissemination of these innovations. The following areas will require special attention during the *Amrit Kaal*:

- *Start with reforms in agriculture education*. Make drastic changes in the curriculum and offer extensive hands-on training to agri-extension students on digital tools. Create a separate course on digital agriculture right away.

- *Create a new cadre of advisors* at the district level whose task may be to guide farmers in accessing technology, new knowledge and information.

- *Digital Transformation:* Embrace digital technologies and platforms to enhance the delivery of extension services, provide access to information, training, and expert advice, and blend them with the supply of time-critical inputs.

- *Data-driven Decision Making*: Leverage data analytics and remote sensing technologies to collect and analyze agricultural data, weather patterns, and market trends. And to provide personalized advice and recommendations to farmers, helping them make informed decisions about crop selection, pest management, irrigation, and market opportunities.

- *Knowledge Networks and Communities of Practice*: Facilitate the formation of online and offline knowledge networks and communities of practice. Encourage farmers, researchers, and extension professionals to share experiences, best practices, and innovative solutions. This can foster peer learning, collaboration, and the dissemination of localized knowledge.

- *Participatory and Farmer-Centric Approaches*: Shift from a top-down approach to a participatory and farmer-centric model. Involve farmers in co-creating extension programs and initiatives, ensuring their needs, preferences, and feedback are incorporated. Encourage farmer-to-farmer knowledge exchange and learning through farmer field schools, study circles, and demonstrations. Promote and transform Farmer Producer Organizations (FPOs), Farmer Producer Companies (FPCs), and Agricultural Cooperatives (ACs) into Smart Production and Aggregation Centers.

- *Strengthen agricultural extension services*: Equip extension advisors with the knowledge and tools to promote climate-smart and sustainable agriculture practices. Help farmers adopt resilient farming techniques, conserve natural resources, reduce greenhouse gas emissions, and mitigate the impacts of climate change. Guide organic farming, agroforestry, water management, and biodiversity conservation. It would require continuous investment in the capacity building of extension advisors to enhance their knowledge and skills. Offer regular training programs on emerging technologies, innovative practices, and communication strategies. Foster partnerships with academic institutions, research organizations, and private sector entities to facilitate knowledge transfer and professional development.

- *Value Chain Development*: Expand the scope of extension services beyond production to include post-harvest management, value addition, and market linkages. Help farmers understand market demands, facilitate access to finance and technology, and support establishing farmer-producer organizations. Encourage entrepreneurship and the development of agribusiness enterprises. Strengthen the extension in upstream, midstream, and downstream with collaborations harnessing emerging AgTech and start-up ecosystems.
- *Behavioral Change Communication*: Apply behavioral change communication techniques to influence farmers' attitudes and behaviors. Use social marketing campaigns, interactive media, and community engagement to promote adopting new practices, such as improved nutrition, gender equality, and sustainable farming techniques.
- *Women Empowerment in Agriculture*: Recognize and promote women's vital role in agriculture. Develop gender-sensitive extension programs that address women farmers' specific needs and constraints. Offer training and support in areas such as financial literacy, credit access, and farm management decision-making.
- *Provide greater space and an enabling environment for the private sector* to access public resources and technologies.

6. Epilogue

The role of agriculture, including agricultural research, education, and extension, is immense in transforming India into a developed nation by 2047. It is envisioned that by 2047, India would emerge as a *Vishwaguru* in the agricultural research, education, and extension system. The success will rely on how the research, education, and extension system responds to the changing scenario. To accomplish the task, the system should fulfill following objectives: (a) develop efficient, self-rejuvenating, diversified, integrated but economical production systems that generate income for farmers which is equivalent to other sectors; (b) enhance genetic potential of different crops, livestock and fish; (c) preserve and protect integrity of natural ecosystems to maintain sustainable growth in production and profitability by optimizing the use of natural resources and man-made inputs; (d) introduce non-degrading quality agricultural practices for sustaining health of air, water and soil (minimum tillage, crop residue recycling, diversification, integrated farming practice, etc.); and (e) increase input use efficiency in food production, distribution, consumption and beyond to respond to societal needs and environmental concerns.

There are a few conditions to accomplish the vision of India by 2047. These include (a) develop and prioritize phase-wise clear goals and targets; (b) allocate sufficient financial resources to high priority areas; (c) develop state-of-art science infrastructure; (d) improve skills of scientists to keep pace with rapidly changing developments; (e) build multi-disciplinary and multi-institutional partnerships; (f) collaborate with advance research and education institutions at national and global levels; (g) reform agricultural education and agricultural extension system; (h) adopt differentiated and disaggregated approach to develop improved technologies; and (i) policy reforms to effectively implement changing structure of agricultural research, education and extension system.

It is expected that during the *Amrit Kaal*, the Indian agricultural research, education, and extension system will play a key role in transforming India into a developed country. However, this will only be possible if adequate financial resources are allocated to these systems. They should be supported by skilled human resources and enabling policies to leapfrog to a new and higher frontier in agricultural research, education, and extension.

7. References

Aggarwal, P., Roy, J., Pathak, H., Kumar, N. S., Venkateswarlu, B., Ghosh, A., & Ghosh, D. (2022). Managing climate risks in agriculture (pp. 84). In R. Chand, P. Joshi, & S. Khadka (Eds.), Indian agriculture towards 2030. Singapore: Springer Nature.

Agritecture. (2018, May 3). 3D ocean farm seeks to reshape aquaculture. https://www.agritecture.com/blog/2018/5/3/3d-ocean-farming

Indian Council of Agricultural Research (ICAR). (2015). ICAR Vision 2050. Indian Council of Agricultural Research. https://icar.org.in

National Academy of Agricultural Sciences (NAAS). (2022). Road map for rehabilitation of 26 MHa degraded lands in India: Policy paper No. 117 (15 pp.). National Academy of Agricultural Sciences.

NAAS. (2022). Impact of national agricultural research system on Indian economy (pp. 95). National Academy of Agricultural Sciences.

NITI Aayog. (2023). Working group report on crop husbandry, agricultural inputs and supply. NITI Aayog.

Worldometer. (2024). World population projections. https://www.worldometers.info/world-population/world-population-projections/

2 Crop Sector

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1. Introduction

The most important scientific development of the last century has been the advancement of Genetics, particularly the crop genetics that paved foundations for food and nutritional security across the globe. As the world is facing unprecedented challenges in ensuring global food security, with the global population projected to reach 10.3 billion in the mid-2080s (UNDESA, 2024) and climate change impacting crop yields and stability (Nkonya, 2019), India embarks on the 'Era of Elixir' (*Amrit Kaal*), a 25-year journey (2022-2047) towards holistic development and self-reliant India (*Atmanirbhar Bharat*), ensuring food security for its 1.38 billion population (Chand and Singh, 2023). Crop genetics and breeding have been crucial not only in enhancing agricultural productivity and resilience, but necessary to provide sustainable solutions for increasing production across all crops. In India, agriculture contributes 18.2% to the country's GDP and employs 45.6% of its workforce (GoI, 2024). To address the rising challenges of climate change, depleting natural resources including water scarcity, soil degradation, and increasing demand for food, advanced genetic tools have become essential for improving crop yield, quality, and resilience. Nonetheless, yields in many Indian staple crops, like rice and wheat, remain below global standards, highlighting the scope for strategic crop improvement programmes. Although the past century has witnessed significant genetic advances in crop yields

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(Fischer and Edmeades, 2010), leading to *Green Revolution* in India with notable production successes in wheat and rice (Swaminathan, 2006), the rate of yield improvement has slowed down in recent years (Ray *et al*. 2013).

Currently, the prioritized areas for Indian crop genetics and breeding research include development of nutritionally enriched varieties having high yield and climate-resilience along with amenability to mechanization through utilization of precision breeding approaches. Modern plant breeding employs a range of genomic techniques, including molecular markers, quantitative trait loci (QTL) mapping, genomic selection and genome editing to select desired traits, such as resistance to biotic/abiotic stresses, better processing and nutritional quality, enabling faster development of varieties that are better adapted to changing environment. Accelerated breeding, the technique to produce multiple plant generations within a short period, can integrate these approaches to dramatically reduce the time required to introduce improved varieties. Customized breeding schemes are now being framed to improve genetic gain as never before. For instance, 'speed breeding' technique is being used to significantly shorten breeding cycles of frontline crops such as rice, wheat, maize, chickpea and pigeon pea that are vital to India's food security and economic stability (Kabade *et al*. 2023; Samineni *et al*. 2020; Gangashetty *et al*. 2024, Pasala *et al*. 2024). The last two decades have witnessed development of a large number of modern crop varieties with improved traits such as drought tolerance (Cooper and Messina 2023, Azrai *et al*. 2024), enhanced nutritional content (Bouis *et al*. 2024), and resistance to pests and diseases (Jones *et al*. 2024). These varieties have shown promising integration of improved yield, stability, resilience and grain quality (Ellur *et al*. 2025, Mishra *et al*. 2025). Genome editing tools like Clustered Regularly Interspaced Short Palindromic Repeats-CRISPR-associated protein9 (CRISPR-Cas9) also bring new promise in crop improvement. Enhancement of nutrient content in staple crops, addresses challenges of malnutrition prevalent in rural India. Biofortified crop varieties, such as those fortified with minerals and vitamins could support India's nutritional targets (Bollinedi *et al*. 2020, Yadava *et al*. 2023). The incorporation of machine learning in genomics further optimizes breeding by predicting favorable genetic traits, thereby making breeding processes more accurate and efficient (Shahhosseini *et al*. 2021). Such advancements position India to achieve a resilient, sustainable agricultural system, ensuring food security and economic prosperity as the country enters *Amrit Kaal* (Chand and Singh, 2023).

This chapter explores the current state of crop genetics and breeding in India, challenges in crop improvement, emerging trends and technologies, and future directions for ensuring food security during the *Amrit Kaal*. Opportunities of utilizing innovative tools and techniques, such as genome editing and synthetic biology, to transform crop improvement towards ensuring sustainable food and nutritional security are also discussed.

2. Current State of Crop Genetics and Breeding

A strong crop improvement programme in India, supported by advancements in production technologies, conducive policy frameworks, involvement of extension workers and farmers have played a critical role in ensuring food security, since the *Green Revolution* (Swaminathan, 2007). However, there are significant challenges such as the decline in genetic diversity due to focus on high-yielding varieties, making crops more vulnerable to diseases, pests and climate change. Traditional varieties are often neglected, risking the loss of indigenous genetic resources. Climate change introduces erratic weather patterns that existing crops may not withstand. Nutritional quality has been overshadowed by yield, with crops diversification receiving insufficient attention. Additionally, the availability of quality seed at an affordable price to smallholder farmers is still a challenge.

The *Green Revolution* of the 1960s, one of the most significant technological breakthroughs, ushered an era of high productivity, driven by the widespread cultivation of high-yielding miracle wheat varieties such as Kalyansona, Sonalika and rice varieties such as IR8 and Jaya. Concerted breeding efforts over the past six decades have led to the development and release of numerous high yielding crop varieties suited to different ecologies. However, the current rate of yield improvement falls short of meeting the demands of the burgeoning population. Although plant breeding has played a key role in enhancing rice productivity, the efficiency of breeding strategies must be continuously assessed, evaluated and improved steadily in quantitative terms.

Strategic and applied research in crop improvement has enabled substantial improvement in production of agricultural crops since independence (Table 1). The food grain production of 332.20 Mt during 2023-2024 is a quantum jump of 4.7 times as compared to 69.0 Mt in 1950-1951.

Concomitantly, the production of cereals increased by 9.3-fold from 27.0 Mt to 251.0 Mt, pulses by 3-fold to 24.25 Mt, oilseeds by 7.7-fold to 40 Mt, fiber crops by 6.7-fold to 42.21 Mt and sugarcane by 8.0-fold to 453.16

Table 1. Improvement in production of food grains since 1950s

Crops	Area (Mha)		Production (Mt)		Productivity (Kg/ha)	
	1950-51	2023-24	1950-51	2023-24	1950-51	2023-24
Rice and Wheat	40.56	79.65	27.02	251.12	665	3221
Nutri/ Coarse Cereals	37.67	24.92	15.36	56.94	408	2283
Pulses	19.09	27.51	8.41	24.25	441	881
Oilseeds	10.73	30.19	5.16	39.67	481	1314
Fibers	6.45	13.11	6.35	42.21	1131	3173
Sugarcane	1.71	5.74	57.05	453.16	33422	78593

tonnes (Table 1). With the total cropped area showing non-significant increase during this period, this quantum jump in production was made possible through sustained efforts in crop improvement research. The productivity of the cereal crops such as rice and wheat improved by a factor of 4.8, coarse cereals such as maize, sorghum and pearl millet by a factor of 5.6, pulses including chickpea, pigeonpea and lentil by factor of 2.0, oilseeds such as groundnut, rapeseed-mustard, soybean, sunflower, sesame, linseed, niger, safflower and castor by a factor of 2.7, fiber crops like cotton, jute, mesta and sugarcane by a factor of 2.4. Among the cereals, the production trend in rice, wheat, maize, pearl millet and sorghum has shown that the improvement of productivity has been sustained after the *Green Revolution* leading to increased production (Yadav *et al*. 2019).

The high yielding varieties (HYVs) and heterotic hybrids were developed through systematic breeding in various institutes of Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs) (Singh *et al*., 2016). Since 1969, a total of 6563 improved crop cultivars across field crops have been developed by ICAR (Table 2). Among these, 2661 varieties were released during the last decade which were specifically bred for resilience to climate change induced biotic stresses such as diseases and pests, as well as abiotic stresses such as drought, heat and flood conditions. Notably, 537 of these are multi-stress tolerant cultivars offer resistance/ tolerance to two or more stresses. From a food deficit to food surplus and exporting nation, the Indian agriculture witnessed an astounding journey steered by ICAR led National Agricultural Research Education and Extension System (NAREES).

Table 2. The details of improved crop varieties released by ICAR, New Delhi since 1969

Crops	No. of varieties released (1969-2024)	Climate resilient varieties (2014-24)
Cereals	2777	646
Oilseeds	933	217
Pulses	1030	214
Fibre crops	460	89
Forage crops	210	81
Sugar crops	134	32
Other crops	43	2
Total	**6563**	**2661**

2.1. Molecular breeding for crop varietal improvement

Phenotypic selection has been the mainstay of breeding in crops which has helped in development of improved crop varieties in India. However, breeding through phenotypic selection, also known as 'conventional breeding' takes nearly 10-12 years to develop a suitable cultivar (Singh *et al*., 2011). With the advent of molecular marker technology, the breeding cycle has been significantly reduced to 4-5 years by employing marker assisted selection (MAS) (Collard and Mackill, 2008; Singh and Singh, 2015; Hossain *et al*., 2023). In MAS, target gene(s) or QTL is/are selected with the aid of tightly linked- or gene-based- or functional-marker, which ensures precise selection of target genomic region, and avoids linkage drags (Stuber *et al*., 1999). Additionally, gene pyramiding through introgression of multiple genes into a single genetic background has been made possible through selection of desirable plants possessing favourable alleles at the target loci at the seedling stage much before expression of the trait(s). Besides, time-consuming, cumbersome, and costly phenotyping during the breeding process can also be overcome to an extent in molecular breeding.

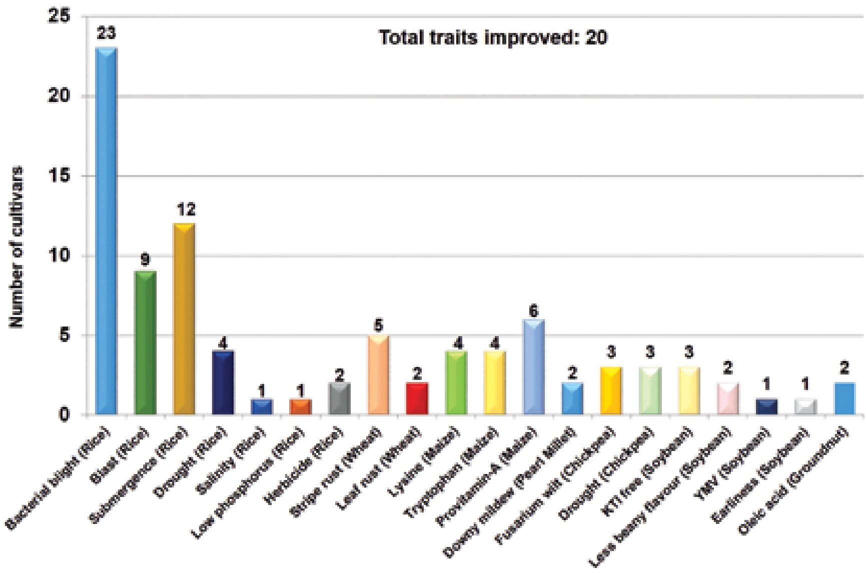
The development and availability of robust molecular marker systems and dense molecular genetic maps have led to the increased application of molecular breeding across field crops in India. Molecular breeding in India was first initiated during 2000 in two major cereals *viz*., rice and maize (Joseph *et al*., 2004; Babu *et al*., 2005). Later, it has been extended to other crops. Specific funding from organizations *viz*, ICAR, SAUs, Department of Biotechnology (DBT) and Department of Science and Technology (DST) have strengthened the research on molecular breeding in India. To further accelerate the development of MAS-derived cultivars, ICAR initiated a 'Consortia Research Project on Molecular Breeding' involving seven crops (rice, wheat, maize, chickpea, mustard, tomato and cucumber) during 2015-26. Across crops, several traits such as resistance to diseases (bacterial blight, blast, leaf rust, stripe rust, wilt, downy mildew and yellow mosaic virus), tolerance to abiotic stresses (drought, water-submergence, salinity and low phosphorus), tolerance to herbicide application, and better nutritional quality (high lysine, tryptophan, provitamin-A, vitamin-A, oleic acid, low phytate, free from trypsin inhibitor and less beany flavour) and early maturity have been introgressed through molecular breeding.

In India, 'HHB-67 Improved' was the first MAS-derived hybrid variety of pearl millet released in 2005 with resistance to downy mildew conferred by two QTL (*qRSg1* and *qRSg4*). 'Improved Pusa Basmati-1' released in 2007 earned the distinction of first MAS-derived rice cultivar possessing *xa13* and *Xa21* genes for resistance to bacterial blight (Gopalakrishnan *et al*. 2008). This marked the significant milestone in the history of Indian plant breeding. Further, marker assisted backcross breeding was effectively used to improve the leading Basmati rice varieties namely, 'Pusa Basmati 1', 'Pusa Basmati 1121', 'Pusa Basmati 6' and 'Pusa Basmati 1509' for resistance to biotic stresses. The bacterial blight resistant varieties namely, 'Pusa Basmati 1718' (Pusa Basmati 1121 + *xa13*+*Xa21*) and 'Pusa Basmati 1728' (Pusa Basmati 6 + *xa13* + *Xa21*) (Ellur *et al*. 2016), blast resistant varieties namely, 'Pusa Basmati 1637' (Pusa Basmati 1 + *Pi9*) (Khanna *et al*. 2015), dual disease resistant (bacterial blight and blast) varieties namely, 'Pusa Basmati 1885' (Pusa Basmati 1121 + *xa13* + *Xa21* + *Pi2* + *Pi54*), 'Pusa Basmati 1886' (Pusa Basmati 6 + *xa13* + *Xa21* + *Pi2* + *Pi54*) (Ellur *et al*. 2025) and 'Pusa Basmati 1847' (Pusa Basmati 1509 + *xa13* + *Xa21* + *Pi2* + *Pi54*) (Sagar *et al*. 2020) were released for commercial cultivation. These varieties have significantly replaced the original varieties. Further, this approach was also used to develop first-ever herbicide tolerant Basmati rice varieties namely, 'Pusa Basmati 1979' (Pusa Basmati 1121 + $AHAS^{rb}$) and 'Pusa Basmati 1985' (Pusa Basmati 1509+$AHAS^{rb}$).

The first MAS-derived maize hybrid, 'Vivek QPM-9' was developed through introgression of *opaque2* gene for enhancement of essential amino acids, lysine and tryptophan (Gupta *et al*. 2013). The first MAS-derived wheat variety, 'PBW-723' (Unnat PBW 343) possessing genes, *Yr17*, *Yr40*, *Lr37* and *Lr57* for resistance to stripe and leaf rusts, was released in 2017. In soybean, the first MAS-based variety, 'NRC-127' with a *Kunitz* trypsin inhibitor (KTI) free trait developed by incorporating null allele of *KTi* was released in 2018. Two MAS-based chickpea varieties *viz*., 'Pusa Chickpea-10216' with drought tolerance having one QTL on LG-4 and 'Super Annigeri-1' possessing *foc4* gene governing *Fusarium* wilt resistance were released together in 2020. Two MAS-derived high oleic acid containing groundnut varieties namely 'Girnar-4' and 'Girnar-5' with *ahFAD2a* and *ahFAD2b* genes were released in 2020.

Molecular breeding has been effectively utilized in India for development of trait specific crop varieties. Till date, 74 varieties developed through molecular breeding have been released in seven crops namely, rice (43), wheat (5), maize (10), pearl millet (2), chickpea (6), soybean (6) and groundnut (2) for various traits (Figure 1) (Yadava *et al*., 2022a). However, including the varieties already identified for release in different crops by AICRP workshops, this number has gone up to 104. These improved varieties also provide high grain yield and are adapted to different agro-ecological conditions of India, thereby providing greater impetus to 'food and nutrition' secure India.

Figure 1. *MAS-derived cultivars released through introgression of traits in different crops using molecular breeding*



2.2. Biofortification of crops

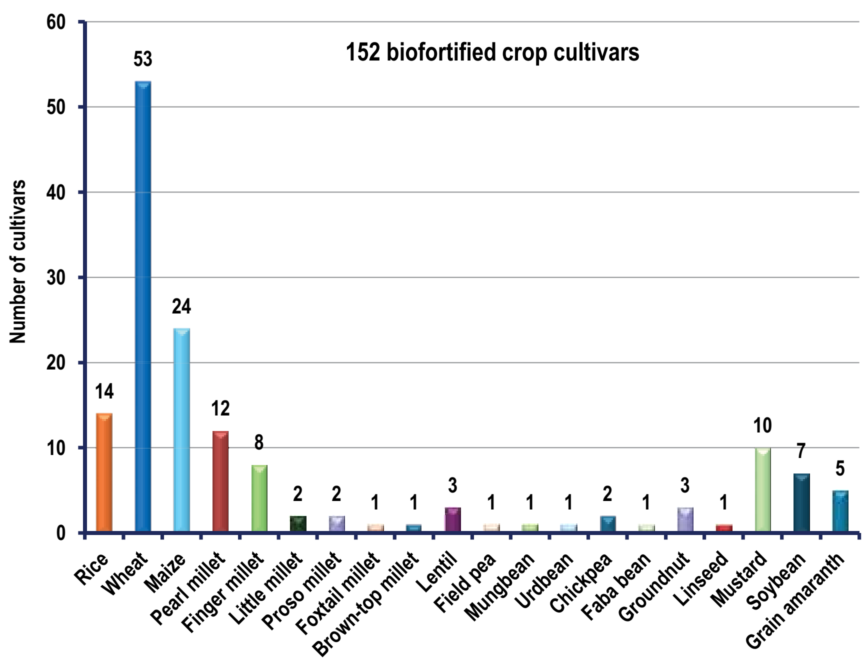
Malnutrition caused by inadequate intake of balanced diet has become major health concern worldwide (Bouis *et al*., 2024). Deficiency of essential nutrients can hinder growth and development, and in severe cases result in mortality with significant socio-economic implications (Hossain *et al*., 2024). Currently, 733 million people suffer from hunger worldwide, while 3.1 billion people are unable to afford healthy food globally (FAO, IFAD, UNICEF, WFP and WHO, 2024). In India, 35.5% children (<5 years) were stunted, while 19.3% and 3.4% were wasted and over-weight, respectively. As high as 57.0% of adult women and 25% men were anaemic (NFHS, 2019-21). Malnutrition in all its forms could cost society up to US$3.5 trillion per year, while India loses US$12 billion owing to deficiency of essential nutrients like vitamins and minerals (www.harvestplus.org). Considering the importance of widespread micronutrient deficiency, world leaders at United Nations included its alleviation as one of the 'Sustainable Development Goals' (SDGs) in 2015 for meeting the current needs without affecting future generations, and mitigate malnutrition in all forms by 2030 (UNDESA, 2023). Combating malnutrition is the most cost-effective step as every $1 invested in proven nutrition programme offers benefits worth $16 (Global Nutrition Report, 2017).

Thus, balanced and nutritious diet for people assumes great significance to mitigate malnutrition (Gupta *et al*., 2015). 'Crop biofortification' – a process of increasing nutrient density in edible seeds through breeding has emerged as the most promising approach over other methods like 'food-fortification', 'medical-supplementation' and 'dietary-diversification' (Yadava *et al*., 2018; Hossain *et al*., 2024). Merits of biofortification include, (i) sustainability, (ii) cost-effectiveness, (iii) availability of nutrition in natural forms, (iv) no negative impact on yield, (v) no need of elaborate infrastructure and distribution system, and (vi) no additional cost on production of biofortified food (Yadava *et al*., 2022b; 2023).

Crop biofortification has been an integral part of research in various ICAR institutes and SAUs (NAAS, 2022). However, to further accelerate the development of biofortified crop cultivars, a 'Consortia Research Platform on Crop Biofortification' has been launched during 2015-26 by the ICAR. Enrichment of essential nutrients namely, iron, zinc, calcium, protein, lysine, tryptophan, provitamin-A, oleic acid and linoleic acid have been the focus of biofortification in different crops. Besides enrichment, the reduction in concentration of anti-nutritional factors namely, phytate, erucic acid, glucosinolates and trypsin inhibitor has also been targeted in different crops (Yadava *et al*., 2022b). Concerted efforts in collaboration with other national and international initiatives has led to the development of 152 biofortified varieties of cereals (rice, wheat, maize, pearl millet, finger millet, little millet, proso millet, foxtail millet and brown-top millet), pulses (lentil, field pea, mung bean, urd bean, chickpea and faba bean), oilseeds (groundnut, linseed, mustard and soybean) and grain amaranth (Figure 2) (Yadava *et al*., 2023; personal communication from ICAR). These biofortified cultivars with balanced concentration of nutrients as well as higher productivity, are the way forward towards achieving country's 'food and nutrition security'.

In rice, 'CR Dhan 311' possesses both high grain protein (10.1%) and zinc (20 ppm). 'Pusa Tejas' is a multi-nutrient-rich (41.1 ppm iron, 42.8 ppm zinc, 12.0% protein) wheat cultivar released for commercial cultivation (Yadava *et al*., 2022b). In maize, several QPM hybrids viz., 'Vivek QPM-9' (lysine: 4.19%, tryptophan: 0.83%), 'Pusa HM4 Improved' (lysine: 3.62%, tryptophan: 0.91%), 'Pusa HM8 Improved' (lysine: 4.18%, tryptophan: 1.01%) and 'Pusa HM9 Improved' (lysine: 2.97%, tryptophan: 0.68%) have been released (Gupta *et al*., 2013; Hossain *et al*., 2018). Besides, 'Pusa Vivek QPM-9 Improved', the world's first multi-nutrient rich maize hybrid with

Figure 2. *Crop-wise biofortified cultivars released in India*



higher provitamin-A and protein quality (provitamin-A: 8.15 ppm, lysine: 2.67%, tryptophan: 0.74%) has been released for commercial cultivation (Muthusamy *et al*., 2014). Maize has also been improved for vitamin-E, and 'Pusa Biofortified Maize Hybrid-5' with enhanced α-tocopherol/ vitamin-E (21.60 ppm), provitamin-A (6.22 ppm), lysine (4.93%) and tryptophan (1.01%) has been released in India (Das *et al*., 2021). In pearl millet, 'HHB-67 Improved 2' possessing high protein (15.5%), besides iron (54.8 ppm) and zinc (39.6 ppm) has been released for commercial cultivation. In legume crops, biofortified lentil, 'IPL 220' (73.0 ppm iron, 51.0 ppm zinc) and in chickpea, 'IPC 2005-62' (27.3% protein) have been released for commercial cultivation. Anti-nutritional factors have also been significantly reduced through breeding. In case of mustard, two anti-nutritional factors like erucic acid and glucosinolates have been reduced below the threshold level (Yadava *et al*., 2022b). Double zero varieties, 'PDZM-31', 'PDZM-33', 'PDZM-35' and 'PDZM 36' possessing both low erucic acid and low glucosinolates have been developed. In soybean, 'NRC-142' is a double biofortified soybean variety with no KTI and lipoxygenase-2 activity.

India also ranked top with 464 research publications on crop biofortification during 2010 to 2021 (Srivastav *et al*., 2022). Among various research and development organizations in India, ICAR published the highest number of research contributions (173) on crop biofortification. Special efforts have been made for popularization of these varieties during past 6-7 years. Large number (>90,000) of front-line demonstrations (FLDs) of these biofortified crop cultivars have been undertaken. Currently, >16 Mha area is under cultivation of biofortified crops in India. Biofortified cultivars have been licensed to >300 private seed companies and farmer producer organizations (FPOs) through >1300 memorandum of understanding (MoU) for seed production and marketing leading to faster spread. Dedication of biofortified crop cultivars on October 16, 2020 (World Food Day), September 28, 2021 and August 11, 2024 by the Hon'ble Prime Minister to the nation is a testimony to the commitment of the country and of the ICAR towards fulfilling country's food and nutritional security.

2.3. Developing crop varieties for industrial applications

Maize has emerged as an important component of crop diversification, especially in areas dominated by crops like rice and wheat. To reduce pollutions caused due to usage of petrol in vehicles, Government of India has decided to blend ethanol to a level of 20% (E_{20}) and 30% (E_{30}) with petrol by 2025 and 2030, respectively. Use of ethanol blended petrol (EBP) would lead to an estimated reduction of carbon monoxide emissions by about 50% in two-wheelers and about 30% in four-wheelers compared to E_0 (neat petrol). Hydrocarbon emissions are estimated to reduce by 20% in both two-wheelers and passenger cars. To meet the E_{20} demand, 1,700 crore litres ethanol needs to be produced of which 850 crore litres would come from dried grains especially from cereals. Among grains, broken rice is used with an ethanol production capacity of 420-425 litres/ tonnes of grains. However, such high volume of broken rice grains is not available as it gets diverted for fortification of rice grains with iron, folic acid and vitamin-B_{12}. Maize grains have emerged as the best alternative for extraction of first generation (1G) ethanol, since India produces 37.1 Mt of maize grains from 11.2 million hectares of land area. However, traditional maize hybrids available in India produce low ethanol with 360-380 litres/ tonne of grains.

On the other hand, waxy maize provides higher starch-ethanol conversion (93.0%) compared to traditional maize (88.2%). Besides, starch extractability of traditional maize available in India is quite low (60-64%) compared to maize in USA (68-70%). Waxy maize provides similar starch extractability as that of USA corn thereby leading to the much higher ethanol production (>450 litres/ tonne of grains) than the traditional corn available in India. This is primarily due to presence of 95-100% amylopectin in waxy maize compared to ~75% in traditional maize (Mishra *et al*., 2025). Recently, ICAR-Indian Agricultural Research Institute (IARI) has released country's first waxy maize hybrid (Pusa Waxy Maize Hybrid-1) developed using introgression of *waxy1* gene through molecular breeding (Talukder *et al*., 2022). Further, dried distillers grain solids (DDGS) is a by-product of the grain-based ethanol extraction process and earns 20% revenues. DDGS made from maize grains is rich in protein and used as an alternative to animal feed. Biofortified maize hybrids such as 'Pusa HQPM-1 Improved' and 'Pusa HQPM-5 improved' developed by IARI were found to possess 38-43% protein in DDGS compared to 28-30% in traditional maize.

Further, 1G ethanol is also produced from stem juice of sweet sorghum. Several sweet sorghum varieties such as 'CSV-49SS', 'CSV-52SS', 'CSV-58SS' and 'CSV-66SS' have been found to suitable for 1G ethanol production. Sweet sorghum is a short duration crop of four months with low water requirement compared to sugarcane, and makes economy of the sugar industries viable due to its wider ecological adaptability. Besides, maize stover can also be used for production of second generation (2G) ethanol. However, stover from traditional maize is a costly source of ethanol primarily due to high lignin present in the dry stalks. Various mutants like *brown midrib* (*bm*) can be used to develop maize hybrids for 2G ethanol. In sugarcane, clones with >15% juice brix and >20% cane fiber is designated as Type-I energy canes. While, Type-II energy canes possess >25% cane fiber and <15% juice brix. Various clones such as 'EC-11002', 'EC-11003', 'EC-11005', 'EC-11008', 'IA-1167' and 'IA-3135' are Type-I energy canes, while 'EC-11001', 'EC-11004', 'EC-11006' and 'EC-11007' are Type-II energy canes. While the juice from sugarcane can be used for direct fermentation in distilleries to produce 1G alcohol, fiber content in canes could be used for 2G ethanol production. However, basic studies on identifying genetic regions for high ethanol recovery and biomass production should be initiated in these targeted crops. Intensive breeding efforts to develop high yielding maize, sorghum and sugarcane hybrids amenable for both 1G and 2G ethanol are required to be undertaken.

2.4. Genome editing for creation of novel alleles through targeted mutagenesis

Genome editing is a biological mutagenic tool to precisely create mutations in the genome of an organism for obtaining desirable traits or repair of genetic defects in an organism. The CRISPR-Cas9 method of genome editing for creation of mutations in the genome of plants, animals and microorganisms with extremely high precision was discovered in 2012 by Emmanuelle Charpentier and Jennifer A. Doudna (Doudna, 2024). They were awarded with the Nobel Prize in Chemistry in 2020, as this technology has revolutionized agriculture and medicine within the very short period.

There are three approaches for genome editing which include Site Directed Nuclease-1 (SDN1), Site Directed Nuclease-2 (SDN2) and Site Directed Nuclease-3 (SDN3). In SDN1 and SDN2, the first generation of mutant plants possess the transgene (gRNA, Cas and selection marker gene) and the desirable mutation. In the second generation, plants with the desired mutation are segregated from the transgene. Thus, mutants developed by SDN1 and SDN2 (including Base Editing and Prime Editing) methods of genome editing are indistinguishable from natural/ induced mutants and free from transgene, and thus are non-GM (non-Genetically Modified). Hence, the products of SDN1 and SDN2 are free from exogenous DNA and are therefore, exempted from rules 7-11 of the Environmental Protection Act, 1986 in India. While, SDN3 mutants are treated like GM plants.

Genome editing has been successfully employed to develop crop plants with desirable agronomically important traits (Zhang *et al*., 2018). China and USA have already developed more than 101 and 78 genome edited genotypes of crops, respectively, followed by Japan and several European countries. As early as 2016, USDA has approved genome edited waxy corn maize and mushroom for cultivation (Demorest *et al*., 2016). The Calyxt soybeans, with 'high oleic' oil with no trans-fats and less saturated fat, developed by genome editing is commercially cultivated and the oil is sold in the market of USA from 2019. In 2021, Japan has permitted genome edited tomato with high levels of gamma-aminobutyric acid (GABA) for commercial cultivation as non-GMO. GABA is believed to aid relaxation and help lower blood pressure (Nonaka *et al*., 2017; Waltz, 2022).

In India, IARI, New Delhi has recently developed abiotic stress tolerant rice variety 'Pusa DST Rice 1' by editing Drought and Salt Tolerance (DST) gene in a mega rice variety, 'MTU1010'. The new variety 'Pusa DST Rice 1' has reduced stomatal density and water use with improved tillering, grain yield, and salt tolerance (Kumar *et al*., 2020). Similarly, ICAR-Indian Institute of Rice Research (ICAR-IIRR), Hyderabad has edited *Cytokinin Oxidase2* (*CKX2*) gene in another mega rice variety, 'Samba Mahsuri' (BPT5204) and developed a new variety named 'DRR Dhan 100' (Kamala) with reduced level of cytokinin oxidase enzyme CKX2 is involved in the degradation of cytokinin, aiding to boost the growth-promoting cytokinin hormone in rice panicle tissue, resulting in higher grain numbers/ panicle, higher nutrient use efficiency, early maturity and higher yield than the parent variety 'Samba Mahsuri'. Both these varieties were tested under the All India Coordinated Research Project (AICRP) on Rice for two years during 2023-24 at 25 locations in the country. While 'Pusa DST Rice 1' showed significantly higher yield under inland salinity (9.6%), alkalinity (14.6%) and coastal salinity (30%) compared to the parent variety 'MTU 1010', 'DRR Dhan 100' (Kamala) recorded 20% higher yield than the parent variety 'Samba Mahsuri' (BPT 5204), besides being nutrient use efficient and 20 days early in maturity. Both these varieties have been identified for release, and were introduced to the nation by the ICAR on May 4, 2025. Cultivating these improved varieties over five million hectares in eastern and southern India could yield 4.5 Mt of additional paddy and save about 7,500 million cubic meters of irrigation water, while reducing greenhouse gas emissions by 20%, as estimated by ICAR.

3. Major Challenges for Crop Improvement in India

Based on the estimates, our country's population is expected to reach 1.6 billion by 2047 from the current population of 1.4 billion. To feed the additional 0.2 billion people, we need to produce 437 Mt of food grains including 333 Mt of rice and wheat, 142 Mt of nutri-/ coarse cereals, 57 Mt of pulses, 55 Mt of oilseeds, and 550 Mt of sugarcane. Notwithstanding this, we need to address impending challenges due to changing climate, reduced availability of water for which we need to improve resource use

Table 3. Current status for food grain production and targets for 2047 to feed our nation

Parameters	2024	2047
Population (Billion)	1.4	1.6
Food grain production (Mt)	332	450
Rice and wheat (Mt)	251	333
Nutri/ coarse cereals (Mt)	57	142
Pulses (Mt)	24	57
Edible oils (Mt)	40	55
Sugarcane (Mt)	453	550

efficiency including water use efficiency to 70% from the present 40% and nitrogen use efficiency from 35% to 60% (Table 3).

Initial plant breeding strategies in India was primarily focused on yield improvement to meet the growing food demand, thereafter, the focus was shifted towards breeding for enhanced tolerance/ resistance to abiotic/ and biotic stresses. Over the time, these increasingly complex traits have been addressed effectively with the advent and incorporation of molecular tools for precision breeding. Despite notable progress in the genetic improvement of crops, there are pressing challenges from time to time, which needs to be addressed to develop sustainable solutions that balance high yields with multiple stress resilience. The major challenges in improving production and productivity of crops include the followings.

3.1. Climate change

Tolerance to abiotic stresses is a multifaceted trait, largely polygenic and intricately woven into the plant's genome. Unlike the relatively straightforward Mendelian inheritance of many of the biotic stress resistance and nutritional quality traits, abiotic stress tolerance has eluded easy categorization, stymied by the challenges of genetic complexity and unreliable screening methodologies. This conundrum has left vast swathes of the global rice-growing areas, particularly within rainfed ecosystems, with not many high-yielding varieties capable of thriving in hostile conditions. In these regions, the relentless cycle of drought exacerbates food insecurity, forcing farmers to rely on traditional, low-yielding cultivars that merely subsist within the boundaries of their genetic endurance. Similar situation exists in other crops too.

3.2. Resource use efficiency

Intensive crop production is water-intensive, soil-exhaustive and labor-demanding. Therefore, to make crop production sustainable, enhancing resource-use efficiency including water, fertilizer, along with reduction in green-house gas (GHG) emissions are of paramount significance. The vulnerability to abiotic stresses like drought and heat, necessitates development of climate resilient high-yielding varieties adapted to these stresses. Addressing these challenges necessitates a deeper exploration of germplasm to unlock the genetic potential of diverse landraces and wild-relatives. Understanding the genetics underlying target traits is pivotal in ensuring the sustainability and productivity of crops in an era of increasing resource constraints.

3.3. Grain quality and nutritional enhancement

Improving the grain and nutritional quality of crops is as critical as enhancing yield. Limited genetic variability especially for minerals such as iron and zinc, coupled with the complex interactions with environment especially with soil, make breeding for improved nutrition difficult. Despite initial setbacks, breakthroughs such as high-protein rice varieties, iron and zinc rich wheat varieties, vitamin-A and essential amino acid -rich maize hybrids and advancements in transgenic approaches have demonstrated promise. The approaches like genome-wide association mapping for nutritional traits to identify potential marker-trait association and genome editing for creating novel allele for use in breeding programme and development of transgenics with enhanced nutrition would pave the way for biofortified crops with enhanced nutrient profiles.

3.4. Emerging pests and diseases

Since the introduction of high yielding crop varieties, breeding for resistance to biotic stresses has become a challenging task for managing emerging diseases and insect-pests causing significant yield losses. With gradual shift in climate, the erstwhile minor diseases and pests are emerging as major threats. Breakdown of resistance in the broad-spectrum resistance gene pyramided lines due to dynamic evolution of new pathotypes/ strains/ biotypes necessitates continued research into their genetics and molecular mechanisms.

3.5. Genetic gain

Over time, breeding approaches such as conventional hybridization, selection, the new plant type concept, hybrid breeding, wide-hybridization, and genomic tools have significantly enhanced crop yields. However, recent trends reveal a concerning stagnation in yield improvement. The pace of genetic gain in grain yield achieved by breeding programmes is insufficient to meet the rising global demand. This slow progress stems largely from a narrow genetic base, a consequence of the extensive reliance on elite × elite crosses, which limits genetic diversity. Furthermore, the intricate genetic and epigenetic interactions governing complex quantitative traits present formidable challenges, impeding the realization of higher genetic gains. Therefore, novel methodologies such as genomic selection has to be essentially incorporated in our breeding programme.

4. Way Forward during *Amrit Kaal*

Following areas need special attention during *Amrit Kaal* to meet the future demand and make India a strong player in crop science research and development:

4.1. Prospecting germplasm and prebreeding

Traditionally cultivated landraces by the farming community are rich sources of desirable genes especially for nutritional quality, biotic and abiotic stress tolerance, while, wild-relatives are regarded as gold-mines of the desirable genes. Evaluating the genetic resources and their prospecting to identify the gene/ QTL are promoters for addressing the newer challenges of crop production. A strong prebreeding programme would provide foundations to develop improved crop cultivars harbouring the desirable target genes for biotic- and abiotic stress tolerance, nutritional quality and productivity.

4.2. Mainstreaming of molecular breeding

Owing to the significant advantage of molecular breeding, several MAS-derived cultivars have been released in rice, wheat, maize, pearl millet, chickpea, soybean and groundnut. However, intensive efforts are required to be undertaken to accelerate the breeding cycle in crops like millets, pulses, oilseeds, fibre crops and even forage crops through molecular breeding. With increasing whole genome sequencing in new crops, genomic resources such as marker information and causal polymorphism in gene(s) are now available in many crops. The information should be readily utilized to improve cultivars in specific crops through molecular breeding. Scientists working in crops where molecular breeding is not currently in use should be trained in the field of molecular breeding by organizing training programmes and workshops. Multi-institutional and multi-disciplinary collaborations are essential to strengthen molecular breeding programmes in the country. So far, the major focus in molecular breeding in majority of crops has been on improving biotic stress resistance to individual diseases and insect-pests and abiotic stress tolerance to individual stresses like drought, salinity, heat and waterlogging. However, in the scenario of climate change, it is now essential to combine higher productivity with multiple biotic- and abiotic- stress tolerance along with nutritional quality by stacking various genes/ QTLs in a single genotype to sustain productivity and profitability to farmers.

4.3. Integration of genome editing

Novel approaches such as genome -editing should be an integral part of the crop improvement programme. Genome editing has great potential to develop crops with improved novel traits that were technically difficult through traditional breeding. For instance, tomato crop was edited to produce provitamin-D3 in fruits, and upon exposure to UV light, provitamin-D3 is converted to vitamin-D3. Wild-relatives of crops can be edited to develop cultivated crop, which otherwise take millions of years to evolution. Wild species of tomato, rice and ground cherry have been edited for accelerated *de novo* domestication (Fernie and Yan, 2019). Landraces and traditional crops varieties can be edited to improve their yield rapidly. Genome editing can significantly boost efficiency, potentially achieving 2.0-4.0% annual gains.

4.4. Intensifying research on crop biofortification

Further research on bioavailabilty on nutrients and retention of nutrients during storage needs to be strengthened in order to provide their full benefits to growers and consumers. Molecular breeding must be embedded in biofortification programme to accelerate the development of biofortified cultivars in crops not targeted so far.

4.5. Improving genetic gain by innovative breeding approaches

4.5.1. Genomic selection

Conventional breeding relying on phenotypic selection and hybridization to improve traits, achieves slow genetic gains of 0.4-1.5% per year, with wheat and maize producing up to 1.0-1.5%. The *Green Revolution* significantly improved yields but required decades to develop new varieties. Hybrid breeding enhances yield through hybrid vigour, producing gains of 1.5-2.5% per year, with maize yields increasing dramatically over the decades. MAS improves precision using DNA markers, resulting in moderate gains of 0.9-1.4% annually, though it's best for traits like disease resistance. Genomic selection accelerates breeding by predicting genetic values, achieving gains of 1.0-2.5%. This range indicates the consistent performance of traditional breeding programmes, besides signifying the potential for improvement through more innovative breeding strategies such as genomic selection.

4.5.2. Speed breeding

Speed breeding technology has been developed to accelerate the breeding cycle in crops (Watson *et al*. 2018). It enables up to six generations of crop in a year in an environment-controlled growth chambers compared to 2-3 generations under glasshouse conditions and one generation under field conditions. In India, speed breeding facilities have been created at IRRI-South Asia Research Centre, Varanasi; National Institute Plant Genome Research (NIPGR), New Delhi; National Agri-Food Biotechnology Institute (NABI), Mohali; Punjab Agricultural University (PAU), Ludhiana and two speed breeding facilities one each at ICAR-IARI, New Delhi and ICAR-Indian Institute of Pulses Research (IIPR), Kanpur are under development, and they will greatly facilitate the genetic gain.

4.5.3. Initiating research on apomixis

Clonal propagation of hybrids through asexual seed production is a dream of plant breeders. Mutation of *OsSPO11-1, OsREC8, OsOSD1* and *OsMATL* genes through a CRISPR/Cas9 genome editing system has led to development of a quadruple mutant AOP (Apomictic Offspring Producer), which produced clonal diploid gametes in rice. Recently, synthetic apomixis has been engineered in rice by combining Mitosis instead of Meiosis (*MiMe*) with the mutation of a sperm-specific *MATRILINEAL* (*MTL*) gene or ectopic expression of paternal gene, *BABY BOOM1* (*BBM1*) in the egg cell, which enables the clonal reproduction of F_1 hybrids through seeds and stable transmission of heterotic phenotypes over generations (Khanday *et al*. 2019). In rice, ectopic co-expression of *OsBBM1* and *DWARF TILLER1 (OsDWT1)*/ *WUSCHEL-LIKE HOMEODOMAIN 9* (*OsWOX9A*) in the egg cells resulted in 86-91% parthenogenesis (Vernet *et al*. 2022). Genome editing of *MiMe* combined with the ectopic expression of *BBM1* in the egg cell led to apomixis.

4.6. Development of designer crops

4.6.1. Development of crop ideotypes suited for mechanization

Development of crop ideotypes such as semi-dwarf early maturing determinate pigeonpea and cotton amenable for large scale mechanization assumes significance. Additionally, herbicide tolerance either through mutating the native gene(s)/ through transgenic approach needs to be initiated and strengthened.

4.6.2. Synthetic biology

It encompasses design and construction of novel artificial biological pathways, organisms or devices, or the redesigning of existing natural biological systems. Thus, synthetic biology has huge potential for modification of primary and secondary metabolisms, and introduction of novel pathways for designing crops. Photosynthesis is the process that sustains life on earth. C_3 photosynthesis is less efficient and conversion to C_4 would help enhance biomass production in stress and resource limited environment. Thus to achieve disruptive change in biomass production for food, feed, fiber and fuel, conversion of C_3 to C_4 is one of the viable options. In India as well as internationally, work is in progress on C_4 rice. Research work on biological nitrogen fixation is also underway, and would pave the way for reducing the dependency on external nitrogen application. Synthetic biology aided conversion is important for development of crops suitable for extreme and degraded soil conditions, bringing non-cultivated plants in to cultivated plants, conversion of non-edible plants to industrial crops for producing raw materials with pharmacological usage.

4.7. Blue-sky research in breeding

'Blue-sky' ideas in crop breeding represent imaginative and visionary concepts aimed at redefining current agricultural methodologies. Adaptive Genomic Breeding leverages advanced genomic techniques to create crops that can modify their genetic expression in response to various environmental stressors such as drought, salinity, and extreme temperatures. The integration of 'Virtual Reality' and 'Augmented Reality' allows breeders to simulate various growth conditions, making it possible to test hypotheses without extensive field trials. This technological synergy paves the way for more efficient breeding processes. Similarly, 'Artificial Intelligence' analyzes vast datasets from genome sequencing and phenotypic observations, optimizing selection processes and accelerating the development of new crop varieties. Innovative concepts such as 'Living Plant Factories' are emerging, where genome-edited crops produce not only food but also high-value materials such as nutraceuticals and biodegradable plastics by manipulating their metabolic pathways. Metabolomics-driven breeding aims to tailor crops based on their specific metabolites, enhancing attributes such as flavor and nutrition. 'Space Agriculture' is an unexplored field by ICAR that should be prioritized to develop crop varieties capable of thriving in extra-terrestrial environments, in collaboration with Indian Space Research Organization (ISRO). These forward-thinking ideas have the potential to significantly enhance food security and the resilience of agricultural system.

4.8. Policy support to biofortified crops

Segregation and assurance of remunerative price for biofortified grains in the market is required to encourage the farmers to grow more biofortified crops. In addition to the cost of cultivation, the nutritional content in biofortified crops should also be accounted for while deciding their minimum support price (MSP). Further, inclusion of these biofortified cereals in different government sponsored programme like National Food Security Mission (NFSM), *Rashtriya Krishi Vikas Yojna* (RKVY) as well as nutrition intervention programme such as Integrated Child Development Services (ICDS) scheme, and 'mid-day meal' would help in providing the much-needed balanced food to poor people.

5. Conclusion

By 2047, plant breeding programmes are expected to undergo a major transformation driven by technological advancements, climate change, and the need for sustainable food systems. The future of plant breeding will be characterized by precision, efficiency, and a deeper integration with environmental and societal needs. Key features of defining plant breeding programmes during *Amrit Kaal* include application of precision breeding, advanced phenotyping and digital breeding platforms, besides development of high yielding climate-resilient biofortified varieties with sustainability.

Precision breeding will heavily rely on ground breaking tools such as CRISPR for genome editing. By 2047, these technologies will be routinely used to develop crops with specific traits, such as drought tolerance, pest resistance, and enhanced nutritional content. This advancement allows breeders to make precise changes in the genome without resorting to the lengthy processes of traditional breeding. Additionally, genomic selection will be fully integrated into breeding programmes, enabling faster and more accurate development of varieties tailored to local environments and climate challenges. The role of AI will be pivotal, as machine learning algorithms will analyze vast datasets to predict complex traits like yield under stress, thus expediting the decision-making process for breeders.

With climate change expected to intensify, plant breeding during *Amrit Kaal* will prioritize varieties that can withstand extreme weather conditions, such as prolonged droughts, floods, salinity and heatwaves. Breeders will aim to create crops adapted to thrive in specific microclimates, ensuring resilience against these unpredictable shifts. Furthermore, new varieties will be designed to adapt seasonally, adjusting their growth and yield potential according to fluctuations in weather patterns.

Sustainability will be at the forefront of new crop development, emphasizing the creation of low-input and high-resilient crops. Breeding programmes will aim to cultivate varieties that require minimal inputs such as water, fertilizers, and pesticides. These crops will be tailored to thrive in low-input farming systems, promoting practices that conserve soil health and biodiversity. The integration of circular economy and low-carbon foot-print principles in breeding will also ensure that new varieties create less waste, and can be utilized in multiple ways, promoting sustainability across the agricultural sector.

The focus on biofortification will lead to the creation of nutrient-dense crops naturally enriched with essential nutrients, thereby helping combat malnutrition and enhance public health. Plant breeding initiatives will delve into developing 'functional foods' that possess bioactive compounds to reduce the risk of chronic diseases like heart disease, diabetes and cancer. These 'super crops' will be tailored for specific health benefits based on their genetic makeup, potentially revolutionizing diet and health. Coupled with advances in nutrigenomics, crops will be tailored to specific populations or individuals, ensuring nutrition is optimized according to genetic predispositions.

Advanced phenotyping and automation will transform how breeding programmes are approached. Automated systems utilizing drones and robotics will monitor crops in real-time, evaluating traits such as plant phenology, abiotic stresses and insect-pest and disease resistance. High-throughput phenotyping platforms incorporating sensors and AI-based technologies will be common place in breeding trials, providing invaluable data. Real-time feedback loops will further enhance breeding efforts, allowing teams to adjust programmes dynamically based on environmental conditions, crop performance and market demands. Breeding simulations will be an essential approach for predicting real-world scenarios without conducting extensive and resource-intensive field trials.

Digital breeding platforms will be essential during *Amrit Kaal*. Integrated digital ecosystems will consolidate genetic, phenotypic, environmental, and market data, empowering breeders to make informed data-driven decisions. Cloud-based global breeding networks will enable collaboration across borders, allowing breeders to share resources and insights in real-time. This collective expertise will accelerate the development of new varieties while tailoring solutions to meet local needs.

With innovative technologies and an emphasis on climate resilience, there is a great potential to address Indian/ global food security challenges. As these programmes develop, it will be crucial to integrate various disciplines, technology, and community needs to shape the agricultural practices of the future. However, success will depend on how quickly the NAREES adopt these changes and implement new technologies in ground-level breeding programmes. It is time to revisit breeding strategies and create new, actionable approaches that can be implemented in Indian breeding programmes to provide nutritional food for the 1.6 billion people projected in 2047.

6. References

Azrai, M., Bahrun, A.H., Efendi, R., Andayani, N.N., Jihad, M., Bahtiar, Zainuddin, B., Muslimin and Aqil, M. (2024). Global drought tolerant maize research and development: Analysis and visualization of cutting-edge scientific technologies. Journal of Agriculture and Food Research, 18:101323. https://doi.org/10.1016/j.jafr.2024.101323.

Babu, R., Nair, S.K., Kumar, A., Venkatesh, S., Sekhar, J.C., Singh, N.N., Srinivasan, G. and Gupta, H.S. (2005). Two-generation marker-aided backcrossing for rapid conversion of normal maize lines to quality protein maize (QPM). Theoretical and Applied Genetics, 111:888-897. https://doi.org/10.1007/s00122-005-0011-6.

Bollinedi, H., Vinod, K.K., Bisht, K., Chauhan, A., Krishnan, S.G., Bhowmick, P.K., Nagarajan, M., Rao, D.S., Ellur, R.K. and Singh, A.K. (2020). Characterising the diversity of grain nutritional and physico-chemical quality in Indian rice landraces by multivariate genetic analyses. Indian Journal of Genetics and Plant Breeding, 80(01):26-38. Doi: 10.31742/IJGPB.80.1.4

Bouis, H., Foley, J., Lividini, K., Jumrani, J., Reinke, R., Straeten, D.V.D., Zagado, R., Boy, E., Brown, L.R., Mudyahoto, B., Alioma, R., Hussain, M. and Pfeiffer, W.H. (2024). Biofortification: Future Challenges for a Newly Emerging Technology to Improve Nutrition Security Sustainably. Current Developments in Nutrition, 8(12):104478. https://doi.org/10.1016/j.cdnut.2024.104478.

Chand, R., and Singh, J. (2023). From Green Revolution to Amrit Kaal - Lessons and Way Forward for Indian Agriculture. National Institution for Transforming India, Government of India, New Delhi, NITI Working Paper 02/2023.

Collard, B.C.Y. and Mackill, D.J. (2008). Marker-assisted selection: an approach for precision plant breeding in the twenty-first century. Philosophical Transaction of Royal Society B: Biological Sciences, 363:557-572. doi: 10.1098/rstb.2007.2170.

Cooper, M. and Messina, C.D. (2023). Breeding crops for drought-affected environments and improved climate resilience. The Plant Cell, 35(1):162-186. https://doi.org/10.1093/plcell/koac321.

Das, A.K., Gowda, M.M., Muthusamy, V., Zunjare, R.U., Chauhan, H.S., Baveja, A., Bhatt, V., Chand, G., Bhat, J.S., Guleria, S.K., Saha, S., Gupta, H.S. and Hossain, F. (2021). Development of maize hybrids with enhanced vitamin-E, vitamin-A, lysine and tryptophan through molecular breeding. Frontiers in Plant Sciences, 12: 659381. doi: 10.3389/fpls.2021.659381.

Demorest, Z.L., Coffman, A., Baltes, N.J., Stoddard, T.J., Clasen, B.M., Luo, S., Retterath, A., Yabandith, A., Gamo, M.E., Bissen, J., Mathis, L., Voytas, D.F. and Zhang, F. (2016). Direct stacking of sequence-specific nuclease-induced mutations to produce high oleic and low linolenic soybean oil. BMC Plant Biology, 16(1):225. doi: 10.1186/s12870-016-0906-1

Doudna, J.A. (2024). The CRISPR revolution: can we change genes for the better?. Frontiers for Young Minds, 12:1063878. doi: 10.3389/frym.2024.1063878

Ellur, R.K., Khanna, A., Yadav, A., Pathania, S., Rajashekara, H., Singh, V.K., Gopalakrishnan, S., Bhowmick, P.K., Nagarajan, M., Vinod, K.K., Prakash, G., Mondal, K.K., Singh, N.K. and Singh, A.K. (2016). Improvement of Basmati rice varieties for resistance to blast and bacterial blight diseases using marker assisted backcross breeding. Plant Science, 242: 330-341. DOI: 10.1016/j.plantsci.2015.08.020.

Ellur, R.K., Khanna, A., Yadav, A.K., Magdum, S., Maurya, S.K., Vinod, K.K., Balamurugan, A., Prakash, G., Mondal, K.K., Krishnan, S.G., Nagarajan, M., Velayudhan, P.K., Bhowmick, P.K., Haritha, B., and Singh, A.K. (2025). Development of dual disease resistant Basmati rice varieties offer significant economic advantage and impetus to sustainable crop production. Journal of Advanced Research. https://doi.org/10.1016/j.jare.2025.02.014.

FAO, IFAD, UNICEF, WFP and WHO. (2024). The State of Food Security and Nutrition in the World 2024 – Financing to end hunger, food insecurity and malnutrition in all its forms. Rome. https://doi.org/10.4060/cd1254en

Fernie, A.R. and Yan, J. (2019). De Novo domestication: an alternative route toward new crops for the future. Molecular Plant, 12(5): 615-631. https://doi.org/10.1016/j.molp.2019.03.016.

Fischer, R.A. and Edmeades, G.O. (2010). Breeding and Cereal Yield Progress. Crop Science, 50:S-85-S-98. doi: 10.2135/cropsci2009.10.0564

Gangashetty, P.I., Belliappa, S.H., Bomma, N., Kanuganahalli, V., Sajja, S.B., Choudhary, S., Gaviyappanavar, R., Bomireddy, D., Kumar, V.A., Pranati, J., Sharma, M. and Pandey, M.K. (2024). Optimizing speed breeding and seed/pod chip based genotyping techniques in pigeonpea: A way forward for high throughput line development. Plant Methods, 20: 27. Doi: 10.1186/s13007-024-01155-w

Global Nutrition Report (2017). Nourishing the SDGs. Bristol, UK: Development Initiatives.

Gopalakrishnan, S., Sharma, R., Rajkumar, K.A., Joseph, M., Singh, V.P., Singh, A.K., Bhat, K.V., Singh, N.K. and Mohapatra, T. (2008). Integrating marker assisted background analysis with foreground selection for identification of superior bacterial blight resistant recombinants in Basmati rice. Plant Breeding, 127: 131-139. doi:10.1111/j.1439-0523.2007.01458.x.

Government of India (2024). Economic Survey 2023-24. Ministry of Finance, Department of Economic Affairs, New Delhi. https://www.indiabudget.gov.in/budget2024-25/economicsurvey/doc/echapter.pdf.

Gupta, H.S., Hossain, F. and Muthusamy, V. (2015) Biofortification of maize: An Indian perspective. Indian Journal of Genetics and Plant Breeding, 75:1-22. doi: 10.5958/0975-6906.2015.00001.2.

Gupta, H.S., Raman, B., Agrawal, P.K., Mahajan, V., Hossain, F. and Thirunavukkarasu, N. (2013). Accelerated development of quality protein maize hybrid through marker-assisted introgression of *opaque-2* allele. Plant Breeding, 132: 77-82. https://doi.org/10.1111/pbr.12009s.

Hossain, F., Bollinedi, H., Yadava, D.K. and Singh, A.K. (2024). Nutritional enrichment of crop plants with special reference to quality protein, minerals and vitamins using novel genes of relevance based on conventional and innovative breeding strategies. In: Editors: Muralidharan *et al*. Proceedings of one-day dialogue on 'Identification and utilization of novel genes of value and relevance for improvement of crop varieties to face future challenges to Indian agriculture'. ISBN 978-81-936934-8-3. pp. 250-267.

Hossain, F., Jaiswal, S.K., Muthusamy, V., Zunjare, R.U., Mishra, S.J., Chand, G., Bhatt, V., Bhat, J.S., Das, A.K., Chauhan, H.S. and Gupta, H.S. (2023). Enhancement of nutritional quality in maize kernel through genomics-assisted breeding for vte4, crtRB1 and opaque2 genes. Journal of Applied Genetics, 64, 431-443. doi.org/10.1007/s13353-023-00768-6.

Hossain, F., Muthusamy, V., Pandey, N., Vishwakarma, A.K., Baveja, A., Zunjare, R., Thirunavukkarasu, N., Saha, S., Manjaiah, K.M., Prasanna, B.M. and Gupta, H.S. (2018). Marker-assisted introgression of opaque2 allele for rapid conversion of elite hybrids into quality protein maize. Journal of Genetics, 97:287-298. https://doi.org/10.1007/s12041-018-0914-z.

Nkonya, E.M. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla *et al*. (eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA, 896 pp. doi: 10.1017/9781009157988.

Jones, J.D.G., Staskawicz, B.J. and Dangl, J.L. (2024). The plant immune system: From discovery to deployment. Cell, 187, 2095-2116. Doi: 10.1016/j.cell.2024.03.045

Joseph, M., Gopalakrishnan, S., Sharma, R.K., Singh, V.P., Singh, A.K., Singh, N.K. and Mohapatra, T. (2004). Combining bacterial blight resistance and Basmati quality characteristics by phenotypic and molecular marker-assisted selection in rice. Molecular Breeding, 13:377–387.

Kabade, P.G., Dixit, S., Singh, U.M., Alam, S., Bhosale, S. Kumar, S., Singh, S.K., Badri, J., Varma, N.R.G., Chetia, S., Singh, R., Pradhan, S.K., Banerjee, S., Deshmukh, R., Singh, S.P., Kalia, S., Sharma, T.R., Singh, S., Bhardwaj, H., Kohli, A., Kumar, A., Sinha, P. and Singh, V.K. (2023). SpeedFlower: A comprehensive speed breeding protocol for indica and japonica rice. Plant Biotechnology Journal, 22:1051-1066. doi: 10.1111/pbi.14245

Khanday, I., Skinner, D., Yang, B., Mercier, R. and Sundaresan, V.A. (2019). Male-expressed rice embryogenic trigger redirected for asexual propagation through seeds. Nature, 565:91-95.

Khanna, A., Sharma, V., Ellur, R.K., Shikari, A.B., Gopala Krishnan, S., Singh, U.D., Prakash, G., Sharma, T.R., Rathour, R., Variar, M., Prashanthi, S.K., Nagarajan, M., Vinod, K.K., Bhowmick, P.K., Singh, N.K., Prabhu, K.V., Singh, B.D. and Singh, A.K. (2015). Development and evaluation of near isogenic lines for major blast resistance gene(s) in Basmati rice. Theoretical and Applied Genetics, 128:1243-1259. DOI: 10.1007/s00122-015-2502-4.

Kumar, V.V.S., Verma, R.K., Yadav, S.K., Yadav, P., Watts, A., Rao, M.V. and Chinnusamy, V. (2020). CRISPR-Cas9 mediated genome editing of drought and salt tolerance (*OsDST*) gene in *indica* mega rice cultivar MTU1010. Physiology and Molecular Biology of Plants, 26(6):1099-1110. doi: 10.1007/s12298-020-00819-w

Mishra S.J., Hossain F., Zunjare R.U., Chhabra R., Katral A., Gopinath I., Bhatt V., Sarma G.R., Talukder Z.A., Kasana R.K., Devi E.L., Sarika K., Mehta B.K., Guleria S.K., Kumar J. and Muthusamy V. (2025). Genomics assisted stacking of waxy1, opaque2, and crtRB1 genes for enhancing amylopectin in biofortifed maize for industrial utilization and nutritional security. Functional and Integrative Genomics, 25:18. https://doi.org/10.1007/s10142-024-01523-8.

Muthusamy, V., Hossain, F., Thirunavukkarasu, N., Choudhary, M., Saha, S., Bhat, J.S., Prasanna, B.M. and Gupta, H.S. (2014). Development of β-carotene rich maize hybrids through marker-assisted introgression of β-carotene hydroxylase allele. PLoS One, 9(12):e113583. doi:10.1371/ journal.pone.0113583.

NAAS (2022). Biofortification to Address Malnutrition in India: Present status and way forward. Strategy Paper No. 17, National Academy of Agricultural Sciences, New Delhi: 23 p.

National Family Health Survey-5 (2019-21). Ministry of Health and Family Welfare, Govt. of India.

Nonaka, S., Arai, C., Takayama, M., Matsukura, C. and Ezura, H. (2017). Efficient increase of γ-aminobutyric acid (GABA) content in tomato fruits by targeted mutagenesis. Scientific Reports, 7: 7057. https://doi.org/10.1038/s41598-017-06400-y.

Pasala, R., Chennamsetti, M., Patil, B., Kadirvel. P., Geethanjali, S., Nagaram, S., Sajja, S., Vennapusa, A.R., Prasad, P.V. and Mathur, R.K. (2024). Revolutionizing Crop Production: The Imperative of Speed Breeding Technology in Modern Crop Improvement. Crop Breeding, Genetics and Genomics, 6(2), e240003. Doi: 10.20900/cbgg20240003

Ray, D.K., Mueller, N.D., West, P.C. and Foley, J.A. (2013). Yield trends are insufficient to double global crop production by 2050. PLoS One, 8(6):e66428. doi: 10.1371/journal.pone.0066428

Sagar, V., Dhawan, G., Krishnan, S.G., Vinod, K.K., Ellur, R.K., Mondal, K.K., Rathour, R., Prakash, G., Nagarajan, M., Bhowmick, P.K., Bollinedi, H. and Singh, A.K. (2020). Marker assisted introgression of genes governing resistance to bacterial blight and blast diseases into an elite Basmati rice variety, 'Pusa Basmati 1509'. Euphytica, 216(1):1-8. doi: https://doi.org/10.1007/s10681-019-2549-4.

Samineni, S., Sen, M., Sajja, S.B. and Gaur, P.M. (2020). Rapid generation advance (RGA) in chickpea to produce up to seven generations per year and enable speed breeding. The Crop Journal, 8(1):164-169. Doi: 10.1016/j.cj.2019.08.003

Shahhosseini, M., Hu, G., Huber, I. and Archontoulis, S.V. (2021). Coupling machine learning and crop modeling improves crop yield prediction in the US Corn Belt. Scientific Reports, 11:1606. doi: 10.1038/s41598-020-80820-1

Singh, A.K., Gopalakrishnan, S., Singh, V.P., Prabhu, K.V., Mohaptra, T., Singh, N.K., Sharma, T.R., Nagarajan, M., Vinod, K.K., Singh, D., Singh, U.D., Chander, S., Atwal, S.S., Seth, R., Singh, V.K., Ellur, R.K., Singh, A., Anand, D., Khanna, A., Yadav, S., Goel, N., Singh, A., Shikari, A.B., Singh, A. and Marathi, B. (2011). Marker Assisted Selection: a paradigm shift in Basmati breeding. Indian Journal of Genetics and Plant Breeding, 71(2):120-128.

Singh, B.D. and Singh, A.K. (2015). Marker-assisted plant breeding: principles and practices. Book – Springer. ISBN No. 978-81-3223-725-9. pp. 514.

Singh, R.B., Chopra, R.K., Singh, A.K., Gopala Krishnan, S., Singh, N.K., Prabhu, K.V., Singh, A.K., Bansal, K.C. and Mahadevappa, M. (2016). Crop Science. In: 100 years of agricultural sciences in India (Ed. Singh RB). NAAS, New Delhi, India. pp. 1-98.

Srivastav, P., Vutukuru, M., Ravindran, G. and Awad, M.M. (2022). Biofortification - present scenario, possibilities and challenges: A scientometric approach. Sustainability, 14:11632. https://doi.org/10.3390/su141811632.

Stuber, C.W., Polacco, M. and Senior, M.L. (1999). Synergy of empirical breeding, marker-assisted selection, and genomics to increase crop yield potential. Crop Science, 39:1571-1583.

Swaminathan, M.S. (2006). An evergreen revolution. Crop Science, 46(5):2293–2303. doi: 10.2135/cropsci2006.9999

Swaminathan, M.S. (2007). Can science and technology feed the world in 2025?. Field Crops Research, 104:3-9.

Talukder, Z.A., Muthusamy, V., Chhabra, R., Bhatt, V., Reddappa, S.B., Mishra, S., Prakash, N., Kasana, R., Chauhan, H.S., Mehta, B., Guleria, S.K., Zunjare, R.U. and Hossain, F. (2022). Enrichment of amylopectin in sub-tropically adapted maize hybrids through genomics-assisted introgression of waxy1 gene encoding granule-bound starch synthase (GBSS). Journal of Cereal Science, 105:103443. doi.org/10.1016/j.jcs.2022.103443.

UNDESA (2023). Division for Sustainable Development Goals, Department of Economic and Social Affairs. United Nations Secretariat Building, 405 East 42nd Street, New York, NY 10017, USA.

UNDESA (2024). World Population Prospects 2024: Summary of Results (UN DESA/POP/2024/TR/NO. 9).

Vernet, A., Meynard, D., Lian, Q. Mieulet, D., Gibert, O., Bissah, M., Rivallan, R., Autran, D., Leblanc, O., Meunier, A.C., Frouin, J., Taillebois, J., Shankle, K., Khanday, I., Mercier, R., Sundaresan, V. and Guiderdoni, E. (2022). High-frequency synthetic apomixis in hybrid rice. Nature Communication, 13:7963. https://doi.org/10.1038/s41467-022-35679-3.

Waltz, E. (2022). GABA-enriched tomato is first CRISPR-edited food to enter market. Nature Biotechnology, 40:9-11. doi: https://doi.org/10.1038/d41587-021-00026-2.

Watson A., Ghosh, S., Williams, M.J., Cuddy, W.S., Simmonds, J., Rey, M., Hatta, M.A.M., Hinchliffe, A., Steed, A., Reynolds, D., Adamski, N.M., Breakspear, A., Korolev, A., Rayner, T., Dixon, L.E., Riaz, A., Martin, W., Ryan, M., Edwards, D., Batley J., Raman, H., Carter, J., Rogers, C., Domoney, C., Moore, G., Harwood, W., Nicholson, P., Dieters, M.J., DeLacy, I.H., Zhou, J., Uauy, C., Boden, S.A., Park, R.F., Wulff, B.BH. and Hickey, L.T. (2018). Speed breeding is a powerful tool to accelerate crop research and breeding. Nature Plants, 4:23-29. doi: 10.1038/s41477-017-0083-8.

Yadav, O.P., Singh, D.V., Dhillon, B.S. and Mohapatra, T. (2019). India's evergreen revolution in cereals. Current Science, 116 (11):1805-1808.

Yadava, D.K., Hossain, F., Choudhury, P.R., Kumar, D., Singh, A.K., Sharma, T.R. and Mohapatra, T. (2022a). Crop cultivars developed through molecular breeding (Second Edition). Indian Council of Agricultural Research, New Delhi. Pp 80. ISBN No. 978-81-7164-247-2.

Yadava, D.K., Choudhury, P.R., Hossain, F., Kumar, D., Sharma, T.R. and Mohapatra, T. (2022b). Biofortified varieties: Sustainable way to alleviate malnutrition (Fourth Edition). Indian Council of Agricultural Research, New Delhi. pp. 106. ISBN NO. 978-81-7164-248-9.

Yadava, D.K., Hossain, F. and Mohapatra, T. (2018). Nutritional security through crop biofortification in India: Status & future prospects. Indian Journal of Medical Research, 148:621-631. DOI: 10.4103/ijmr.IJMR_1893_18.

Yadava, D.K., Hossain, F., Choudhury, P.R., Sharma, T.R. and Mohapatra, T. (2023). Biofortification of Food Crops for Nutrition Security. Indian Journal of Fertilisers, 19 (12):36-42.

Zhang, Y., Massel, K., Godwin, I.D. and Cao, G. (2018). Applications and potential of genome editing in crop improvement. Genome Biology, 19:210. https://doi.org/10.1186/s13059-018-1586-y

3 Horticulture Sector

S. Uma[1] and P. Suresh Kumar[1]

1. Context

India cultivates a diverse range of horticultural crops under tropical, sub-tropical, temperate, dryland, rainfed, and desert conditions, including 115 types of fruits, 60 vegetables, 30 spices, 7 plantation crops, along with numerous medicinal plants and floricultural crops. The expansion of horticultural crops has been steady and rapid, driven by technology and scientific research. Enhancing productivity in horticultural crops is essential for increasing food production and availability. Due to extensive research, technological advancements, and supportive policies, horticulture has become a viable option for small and marginal farmers and has started attracting entrepreneurs for commercial ventures. Significant advancements have happened in horticulture as an industry over the years, which have shaped the present horticulture. These are:

- Horticulture occupies 10% of the land in India, contributes over 34.4% of the agricultural GDP, and supports nearly 20% of the agricultural labor force, but it occupies less than 12.5% of the total cropped area.
- India's diverse geographical features are conducive to cultivating a wide variety of fruits and vegetables.
- India accounts for more than 10% of the world's fruit production, with major contributions from states such as Uttar Pradesh, Odisha, Andhra Pradesh, Tamil Nadu, Gujarat, Maharashtra, and Karnataka, with niche crops in the east and the Himalayan regions.

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[1] ICAR-National Research Centre for Banana, Tiruchirappalli.

We wholeheartedly acknowledge the inputs received from experts and the information extracted from the Vision documents of Horticulture institutes for preparing this chapter.

- The country has vast and diverse agroecological zones, allowing year-round cultivation of various vegetables, such as potatoes, onions, tomatoes, brinjals, cabbages, green peas, and exotic vegetables.
- Favorable climatic conditions in certain regions enable year-round flower production, meeting the increasing demand for flowers, thereby fostering the growth of floriculture as a thriving business.
- In terms of export potential, India's flower market is growing, with the floriculture sector witnessing a compound annual growth rate (CAGR) of approximately 10%. Major flower-exporting countries, including the Netherlands, dominate the global market, which means India should enhance its competitive edge through better quality and marketing strategies. The country's floriculture industry is poised for growth, especially in states like Tamil Nadu, Andhra Pradesh, and Karnataka, which are leading in production and is gaining momentum in Newer areas like Jharkhand, Maharashtra and North Eastern states.
- Technological advancements and research in horticulture have led to improved crop varieties, pest management, and sustainable farming practices, further enhancing productivity and resilience.
- India leads in spices and plantation crops like coconut, tea, coffee, and cocoa. The land's medicinal treasures are explored for traditional medicine and isolation of bioactives.
- Horticulture offers significant employment opportunities, particularly for women and rural communities, contributing to social and economic empowerment.
- Processing and value addition are emerging as critical growth areas, generating enormous employment opportunities.
- Horticulture supports environmental sustainability by promoting biodiversity, efficient land use, and eco-friendly agricultural practices.

For the Indian agricultural economy to achieve a growth rate of 4% per annum to meet the increasing food demand, the horticultural sector should grow at 8% per annum (Chand, 2022). The policy implication is that the robust growth of the horticulture sector relies on aligning production with demand changes, avoiding price distortions, and ensuring well-functioning markets to convey demand signals to producers. In 2047, the demand for horticultural crops will be shaped by a combination of evolving factors, driven by changes in population, demographics, environmental consciousness, dietary preferences, expandable income, energy resilience, urbanization and technological changes. In recent years, urbanization has created a growing need for urban horticulture, including rooftop gardens, vertical farms, and community gardens. This contributes to the demand for horticultural crops within city centers. Consumers increasingly prioritize fresh, organic, and nutritionally rich foods. However, of late, it faces challenges such as climate change, resource depletion, and inefficiencies in supply chains.

During the *Amrit Kaal,* the horticulture sector shall aim to address these issues by setting a strategic framework for sustainable growth. This long-term plan should emphasize adopting advanced technologies, such as automation, mechanization, precision farming, IoT, sensors, drones and biotechnology, to enhance productivity and resilience. It also needs to focus on improving storage, transportation, and market access infrastructure, reducing post-harvest losses and increasing farmers' incomes and consumers' choices.

The horticulture sector needs to transform and become more competitive and sustainable to meet the future demands of a growing population and global markets. With the advent of frontier technologies, a paradigm shift in farming is required to make it more prudent and smarter, align with markets by integrating technological advancements, and move from traditional farming to smart and precision farming.

2. Challenges and Opportunities

2.1. Global horticulture: Trends and opportunities

The global horticulture sector is experiencing significant trends driven by technological advancements, consumer preferences, and urbanization. Precision horticulture is gaining traction, using drones, sensors, and data analytics to optimize water and nutrient use, improving crop monitoring and yield efficiency. Biotechnological innovations, such as tissue culture and genetic engineering (e.g., CRISPR/Cas9), enhance crop traits like pest resistance, drought tolerance, and nutritional value. The organic fruits and vegetables market is also expanding rapidly, projected to reach $103.3 billion by 2025, as consumers prioritize sustainable and health-conscious food options. Urban horticulture, including vertical farms and rooftop gardens, is transforming food production in cities, reducing the carbon footprint and ensuring year-round access to fresh produce. Governments and private sectors increasingly collaborate to promote these innovations, investing in research and infrastructure development to make horticulture more resilient, efficient, and sustainable.

Despite these advancements, the global horticulture sector faces significant challenges, primarily due to climate change, which threatens to reduce crop yields by up to 12% by 2050 as temperatures rise and precipitation patterns shift. This change also facilitates the spread of pests and diseases, potentially causing crop losses of up to 30% in certain regions. Water scarcity is another critical concern, as horticultural crops require substantial water for irrigation, contributing to agriculture's 70% share of global freshwater usage (Pawar and Sakhale, 2022). Sustainable practices like precision irrigation and developing drought-resistant varieties are essential to address this issue. Soil degradation, with 33% of global soils classified as moderately to highly degraded, poses another obstacle, necessitating sustainable soil management strategies such as crop rotation and organic amendments. Labor shortages and the complexity of horticultural production further complicate the situation, underscoring the need for mechanization and automation. The loss of biodiversity from monoculture practices also reduces the resilience of horticultural systems, making diversification and genetic conservation critical strategies for mitigating risks. Opportunities exist in addressing these challenges through technology, government support, and sustainable practices, but a coordinated and innovative approach is vital to ensure the sector's growth and sustainability.

2.2. Indian horticulture sector: Lessons learnt and road ahead

The horticulture sector in India has emerged as an important component in the agricultural landscape, contributing significantly to the country's economy, food security, and rural livelihoods. Horticulture production increased significantly, rising from 25 Mt in 1950-51 to 351.9 Mt in 2021-2022, surpassing food grain production. Currently, horticulture crops are cultivated in 27.5 Mha. Fruits are cultivated on 7.05 Mha, producing 107.24 Mt, while vegetables are grown on 11.35 Mha, producing 204.84 Mt (Anon, 2022).

India's diverse agro-climatic conditions, ranging from temperate to tropical and arid to humid, support the cultivation of various fruits and vegetables throughout the year, enabling continuous production and supply. India is the world's second-largest producer of fruits and vegetables, contributing roughly 12.40% and 13.30% to global fruit and vegetable production, respectively. In the fiscal year 2022-23, export earnings from fresh and processed fruits and vegetables, floriculture, medicinal and aromatic products, and horticultural seeds and planting materials were Rs. 312.76 billion. Additionally, India's total export earnings from crude drugs, herbal extracts, and finished products of medicinal and aromatic crops were approximately Rs. 60.00 billion. Such an impressive performance has been facilitated by the government's emphasis on promoting the horticulture sector through initiatives like the National Horticulture Mission (NHM) and *Rashtriya Krishi Vikas Yojana* (RKVY), which have improved infrastructure, research, and technology adoption.

The government launched the National Horticulture Mission in the 1990s for the holistic growth in the horticulture sector with improved storage, processing and transportation. During this period, emphasis was also given to quality planting material production through tissue culture. However, the real change happened in the new millennium emphasizing enhancing productivity, cold chain development and organic farming. In 2010, with the advent of precision farming and the release of new varieties, India became a significant exporter of fruits, vegetables, flowers and spices. In recent times, emphasis has been given on better crop and land management, climate-smart horticulture using AI, IoT and market-driven data analytics and focus on processing and branding of horticultural products.

Economic reforms and policies in the 1990s promoted diversification towards horticultural crops (Chand *et al.*, 2008). India produces ginger and okra among vegetables and ranks second in potatoes, onions, cauliflower, brinjal, and cabbage. In fruit production, India holds the top position in banana (36.7%), papaya (43.6%), and mango (40.4%), ranks second in cashew, and third in citrus fruits. The growth of the horticulture sector has been distinct from the overall agriculture sector, primarily due to its potential for high-income generation rather than food security.

Recently, there has been a noticeable shift in consumption patterns, favoring fruits, vegetables, and herbal products. Consequently, the supply side should adjust to meet the quantity, quality, and seasonality demand. The domestic demand for fruits and vegetables is projected to be around 930 Mt by 2047-48 (Vision 2050: IIHR). Food demand will be shaped by economic growth and demographic factors, including population growth, urbanization, age distribution, and dietary preferences. Urbanization is projected to rise from 31% currently to around 52% by 2050. Processing is also likely to expand; its growth is expected to rise 10% (Table 1).

Due to their high value and nutraceutical compounds, the per capita demand for spices is expected to increase significantly by 2050. The projected per capita demand for major spices such as black pepper,

Table 1. Current (2022-23) and projected (2047-48) area, production and productivity of horticultural crops

Category	2022-23			2047-48		
	Area	Production	Productivity	Area	Production	Productivity
Fruits	7.0	108.3	15.5	10.5	254.0	24.2
Vegetables	11.4	212.9	18.8	17.0	457.8	26.9
MAP	0.7	0.6	0.9	1.1	1.4	1.2
Flowers	0.3	2.9	10.5	0.4	6.1	15.1
Honey		0.1			0.3	
Plantation crops	4.4	16.1	3.6	6.7	34.5	5.2
Spices	4.3	11.0	2.6	6.5	23.6	3.7
Total	**28.1**	**351.9**	**12.5**	**42.2**	**777.7**	**18.4**

MAP, Medicinal and aromatic plants; Production in Mt; area in Mha; and productivity in t ha^{-1}; Vision 2050: ICAR- IIHR modified

cardamom, ginger, and turmeric is estimated to reach approximately 148 grams, 53 grams, 1.22 kilograms, and 1.63 kilograms, respectively. To meet both local and global demand, production levels for these spices are expected to increase by 2.7 to 5.7 times from current levels.

2.2.1. Strength

To meet higher quality standards and global competition, addressing threats such as deteriorating production environments, fragmented land holdings, and climate change is crucial. Concerted efforts are required to boost productivity and minimize postharvest losses in fruits and vegetables, ensuring quality production even under marginal soil and irrigation conditions. Enhancing input use efficiency is vital. The indigenous germplasm in India includes more than 5000 accessions of fruits, 35000 vegetables, 500 ornamentals, 6000 spices and 8500 medicinal plants (Ud Din and Haseen, 2024). Horticultural crops are seen as a vital component of a balanced and healthy diet, spurring demand. International trade networks have expanded, making a diverse array of horticultural crops available year-round. Consumers enjoy various fruits and vegetables worldwide, increasing the demand for exotic and out-of-season produce. The ageing population and an increase in health-conscious millennials and younger generations result in a higher demand for fruits and vegetables. In addition, changing lifestyles and cultural diversity have driven the demand for a broader range of horticultural products. These shifts have led to a need for more unique and culturally significant fruits and vegetables. The future demand for horticultural crops will be influenced by affordability, nutrition, health, sustainability, and diversity in food choices. The horticulture industry has responded to these requirements with innovative and efficient production methods to ensure a consistent supply of fresh, high-quality produce to meet the population's needs.

In the past, the primary drivers of growth in horticulture sector include:

- Supportive policies and timely reforms have been implemented by both the Central and State Governments.
- Advancements in agricultural research and development (R&D) and the effective dissemination of improved technologies are key.
- Investments from both public sources and private farmers aimed at enhancing irrigation infrastructure.
- Adoption of modern agricultural inputs, such as high-quality seeds/planting materials.
- Availability of institutional credit and subsidies for inputs.
- Strong market support and favorable output pricing.
- Additional factors contributing to this growth could include the development of infrastructure for better storage and transportation, as well as initiatives to foster farmer education and capacity-building.

2.2.2. Challenges

However, the sector still faces challenges such as fragmented land holdings, inadequate post-harvest infrastructure, and limited access to markets and credit for small-scale farmers. Nearly 30-40% of horticultural produce is lost post-harvest due to insufficient cold chain facilities, transportation, and processing infrastructure. Further, meeting the nutritional needs of a rapidly growing population and fulfilling export demands exert significant pressure on the horticulture industry. The goal of producing 930 Mt of horticultural commodities by 2047 requires innovative solutions to address issues such as resource scarcity, shifting weather patterns, and changing consumer preferences.

(i) Climate change and horticulture

Climate change poses a significant environmental challenge with the potential to impact the horticulture sector profoundly. Elevated temperatures combined with erratic precipitation can lead to reduced availability of irrigation water and increased evapotranspiration. This may result in severe water stress for crops, heightened crop water needs, and damage from frost and heat stress. Additionally, climate change can exacerbate issues with insect pests and diseases, and introduce new pests and diseases. Further compounding these challenges are decreasing soil productivity and irregular monsoon patterns, leading to soil erosion, flooding or submergence, and moisture stress.

(ii) Low productivity

A concerning aspect of Indian horticulture is the low productivity across fruits, vegetables, flowers, and medicinal crops. Over the past decade, India has seen a 6.34% increase in fruit and vegetable production and a 4.7% increase in area. Still, productivity has only risen by a modest 1.57%. For fruits, excluding banana and papaya, the average productivity in India stands at 12.0 t ha^{-1}, which is considerably lower compared to leading fruit-producing countries: Indonesia (22.4 t ha^{-1}), the USA (22.2 t ha^{-1}), Brazil (16.1 t ha^{-1}), the Philippines (14.0 t ha^{-1}), and Italy (13.2 t ha^{-1}). Similarly, vegetable productivity in India has been around 17.0 tons per hectare for several years, trailing behind leading producers such as Spain (37.2 t ha^{-1}), the USA (31.4 t ha^{-1}), Iran (26.2 t ha^{-1}), Egypt (25.7 t ha^{-1}), and Italy (25.1 t ha^{-1}). Several factors contribute to this low productivity, including a lack of high-quality planting materials, declining natural resources, resource-constrained farmers, and limited adoption of modern technologies.

For plantation crops like tea, coffee, and rubber, India's productivity lags behind top-producing countries. For instance, India's coffee yield averages around 810 kg ha^{-1}, while Brazil and Vietnam achieve approximately 1,300 and 2,400 kg ha^{-1}, respectively. Similarly, India's tea productivity is about 2,500 kg ha^{-1}, which is lower than countries like Kenya and Sri Lanka, where yields often exceed 3,000 kg ha^{-1}. In the spice sector, the productivity of major Indian spices such as black pepper and cardamom is below global standards. For black pepper, India produces about 325 kg ha^{-1}, while Vietnam, the world leader, manages over 2,000 kg ha^{-1}.

The productivity of flower crops in India presents a mixed picture compared to global standards. As of the 2019-20 season, India cultivated approximately 305,000 hectares of flower crops, yielding about 2.78 Mt. Loose flowers accounted for 2.3 Mt, while cut flowers contributed 762,000 tons. However, India's productivity for flower crops is relatively low compared to leading countries. For instance, the average yield of roses in India is about 11-12 t ha^{-1}, while in the Netherlands, the yield can exceed 50 t ha^{-1}. This discrepancy indicates significant room for improvement in farming techniques, resource management, and overall productivity.

(iii) Degraded and depleted production environment

The average size of landholdings in India has steadily declined, dropping from 2.28 hectares in 1970-71 to 1.55 hectares in 1990-91, and further to 1.23 hectares in 2005-06. During this period, operational holdings have increased from about 70 million to 129 million. The marginal lands often suffer from issues such as moisture and salinity stress (6.73 Mha), acidity (16.03 Mha), and poor soil fertility. Managing these fragile ecosystems involves addressing problems like declining organic matter and nutrient levels, erratic monsoons, groundwater depletion, and deteriorating water quality.

(iv) Plant health management and biosecurity concerns

Serious infestations of insects, pests, diseases, and weeds are significant obstacles in achieving optimal horticultural productivity. These challenges are intensified by changing climate conditions and the emergence of invasive and minor pests and diseases as significant threats. The indiscriminate use of plant protection chemicals exacerbates the problem by fostering resistance among pests and pathogens and contributing to environmental pollution. Furthermore, inadequate quarantine measures in the country will likely exacerbate the risk of introducing new pests and diseases to horticultural crops. The modern detection tools, including high-throughput sequencing, have revealed the presence of a large number of viruses and virus-like pathogens in vegetables, fruit orchards and nurseries.

(v) Post-harvest utilization

Currently, there is a significant gap between the country's production capacity of fruits, vegetables, flowers, and medicinal crops and the infrastructure available for their post-production distribution, storage, and value addition. Scientific approaches drive technological needs that vary greatly depending on production systems, socio-economic conditions, and consumption patterns across the country.

(vi) Changing quality consciousness and global competition

As the purchasing power of the Indian population rises and consumers become increasingly health- and quality-conscious, it is crucial to produce high-quality and safe horticultural products. Additionally, the evolving global trade landscape necessitates that horticultural commodities meet international standards. A significant challenge is the lack of effective quality monitoring mechanisms for the domestic market, which should be addressed to ensure compliance with local and global quality requirements.

(vii) Inadequate market linkage, price fluctuations and infrastructure

The lack of market infrastructure for tracking fluctuating prices is a significant challenge for horticultural producers aiming to achieve better returns. Limited access to credit and the influence of informal lenders impact farmers' decisions regarding the purchase of inputs and the sale of outputs. Additionally, inadequate farming infrastructure increases reliance on weather conditions and creates challenges in marketing and supply chains, particularly for high-value crops.

2.4. Opportunities

Between 1951 and 2021, India's population grew from 35.9 crore to 136.9 crore, while food production (including horticultural commodities) increased from 106 Mt to 936 Mt, more than doubling the rate of population growth. The share of fruits and vegetables in the horticulture sector rose from 12.4% in 1970-71 to 19.4% in 2020-21, reflecting significant sector growth and a decline in cereal contributions from 37.1% to 16.7%. Fruits and vegetables now account for a value comparable to all cereals and pulses combined. Specifically, potatoes and onions, which constituted 15.8% and 5.2% of vegetable output in the 1970s, increased to 27.1% and 11.9% by 2011-20, making up nearly 40% of total vegetable production. The increasing pressure to maximize food production on diminishing cultivable land necessitates adopting precision horticulture, hybrid seeds, protected cultivation, biotechnology, and integrated nutrient and pest management. New strategies should focus on establishing farmer-producer companies or self-help groups (SHGs), creating crop clusters, promoting exports, and developing new plant genotypes. Efficient management of production and surplus, coupled with innovative and competitive technologies, will be crucial for the sector's future (Table 2). These strategies should address sustainability, resource efficiency, support for smallholders, food safety, profitability, and equitable growth.

Table 2. Technological interventions to achieve growth in horticulture

Intervention	Potential contribution (%)
Crop improvement technologies	20-25
Precision production technologies	15-20
Protected cultivation techniques	25-30
Diagnostics and robust seed-based production system	10-15
Post-harvest technologies	25-30
Indigenous crop-based diversified production systems	4-5

3. Vision, Mission, Priorities and Strategic Approaches during *Amrit Kaal*

3.1. Evolving new varieties, genome editing and adopting efficient breeding strategies/ speed breeding

Intensive breeding efforts have led to the development of over 2,000 improved horticultural varieties that offer high productivity, disease resistance, better nutritional quality, and adaptability to diverse agro-climatic conditions. Key varieties that have transformed the horticulture sector include Amrapali mango, Bhagwa pomegranate, triple disease-resistant tomato varieties, Arka Rakshak, leaf curl virus-resistant chillies, high-yielding Bheema Super onions, Arka Kalyan in onion, Arka Prajwal in tuberose, and IISR Prathibha turmeric. Potato varieties such as Kufri Jyoti, Kufri Bahar, Kufri Pukhraj, and Kufri Chipsona-1 account for 75% of the country's potato cultivation, while the anti-browning button mushroom variety DMR-NBS-5 contributes to 32% of total button mushroom production (Patel and Tripathi, 2023). Additionally, 70 traditional horticultural crop varieties in India have been granted Geographical Indication (GI) tags, including mango, citrus, banana, chilli, tea, cardamom, jasmine, grapes, pineapple, brinjal, onion, and coffee.

However, cell culture and genetic transformation came along in the 1980-90s and still remain in the background. While the breeding in the 20th century was largely concentrated on increasing the volume/ yield, subconsciously, we have sacrificed the quality aspects of fruits and vegetables. Further, as the push towards increased yields grew strongly, it also resulted in the use of excess agrochemicals, costing the environment dearly. Hybrid technology has significantly advanced vegetable crop production, with growing demand for hybrid seeds. In the coming years, effective collaboration shall be made with the industry for better market access and penetration of improved varieties for widespread adoption among the farmers.

Genomic tools have revolutionized horticultural crop improvement by enabling precise manipulation and understanding of plant genomes. Techniques such as genome sequencing, marker-assisted selection (MAS), and genome-wide association studies (GWAS) allow researchers to identify and select for desirable traits with greater accuracy. These tools facilitate the identification of genetic markers linked to traits like disease resistance, yield, and quality, accelerating the breeding process. Additionally, advanced methods like CRISPR-Cas9 gene editing enable targeted modifications in plant genomes, allowing new varieties with enhanced traits. The integration of genomic tools in horticulture improves crop resilience and productivity and supports sustainable practices by enabling the development of varieties that require fewer inputs, like water and pesticides.

The real quantum leap, from the days of hybridization and selection, happened when we started venturing into the era of 'omics'. Rapid acceleration of technologies such as whole genome sequencing, single cell transcriptomes, metabolomics, pangenomics, epigenomics, proteomics, and volatilomics is accelerating the 'precision breeding' or focus on speed breeding. Such marker-assisted breeding, quantitative trait loci (QTL) mapping, genotyping by sequencing (GBS), and next-generation sequencing have revolutionized breeding, especially in horticultural crops. For instance, disease resistance markers have been developed in many crops for fungal, bacterial, and viral diseases. When the breeding objective mandates a specific disease resistance, using MAS, any progeny that does not have the marker can be eliminated at the seedling stage itself, thus saving valuable time and space. This is especially handy in perennial crops such as fruits and nuts. Typically, a fruit variety takes 10-25 years before it is released and another 5-10 years to become a popular choice for the growers. When such MAS are used successfully, this long wait can be significantly reduced. Most of the future breeding in horticultural crops will be based on these 'omics' technologies, and conventional breeding remains only in instances where such technology cannot be adapted. But that will be in extremely minor crops.

Precision breeding approach is particularly valuable for improving perennial tree fruit and nut species, where traditional breeding faces challenges due to the complex genetic control of quality traits, long juvenile periods, and the heterozygous nature of their genomes. These advancements are now applied to optimize genome editing with tools like CRISPR/Cas9 systems. By utilizing precision breeding and genome editing, researchers can overcome the limitations of conventional breeding methods, allowing for rapid improvements in cultivars, including enhanced tolerance to abiotic and biotic stresses and better qualitative traits.

Using the protoplast culture, by removing the cell wall, options are opening up to manipulate the cell's genetic material directly, facilitating the introduction of new traits and the study of cellular processes. For example, protoplast culture has been used to develop disease-resistant varieties through somatic hybridization in crops like potatoes and tomatoes, where protoplasts from different species or varieties combine desirable traits. Additionally, this technique also aids in the regeneration of whole plants from single cells, which is essential for cloning and preserving rare or endangered plant species.

Key areas in horticultural biotechnology include genetic transformation, micropropagation, *in vitro* conservation of germplasm, synthetic seed technology, virus elimination, biofertilisers, biopesticides, and postharvest biotechnology. In citrus, meristem culture and micrografting have been successfully used for virus elimination. Embryo rescue techniques have been employed to produce hybrids of *Carica papaya* × *Carica cauliflora*, interspecific crosses in pineapple, and seedless × seedless grape varieties. Diagnostic kits for viruses in banana, citrus, peach, apple, potato and other crops have facilitated the production of disease-free planting material. Research should focus on these areas for developing varieties with higher efficiency.

3.2. Germplasm, mapping new areas and promoting new crops

Around 72,600 accessions of cultivated, wild, and related taxa are currently conserved. Productivity improvement is important to sustain nutritional and food security for an increasing population, which is possible through germplasm enhancement and its utilization. Future food needs could be met by identifying future crops that produce quality produce, better production, higher input use efficiency, provide sustainability, and emphasize carbon-neutral or positive farming.

Expansion of arable lands is not possible. Therefore, potential new areas and disruptive methods for newer crops should be identified. The advent of vertical farming and rapid production systems, such as microgreens, are the best alternative. With emphasis on 'freshness' getting louder by the day, even urban centers of the world are driven to produce crops within their city limits, rather than waiting for a delivery to happen from elsewhere. Vertical farms are emerging in many parts of the world and are fairly successful. The relatively new concept of 'microgreens' has complemented such vertical farming concepts, which have resulted in the rapid cycling of fresh herbs and greens in a 2–3-week cycle, thus increasing the production efficiency. Microgreens, miniature versions of edible greens harvested just after the cotyledon leaves have developed, have surged in popularity for their concentrated flavours, vivid colours, and dense nutrient profiles. Beyond their culinary appeal, microgreens are dense in vitamins, minerals, and antioxidants, providing a convenient and sustainable way to enhance the nutritional content of food.

Increasing the cultivation area for minor fruits and vegetables can be achieved through targeted interventions such as providing farmers with subsidies, technical assistance, and capacity-building programs. Consumer awareness campaigns can stimulate demand and create market opportunities by highlighting these crops' nutritional benefits and culinary versatility. Additionally, leveraging the nutraceutical potential of minor fruits and vegetables offers value addition and market differentiation avenues. Research and development efforts between agricultural researchers, food technologists, and the pharmaceutical sector to identify and harness bioactive compounds, antioxidants, supplements, and functional properties in these crops can unlock opportunities in the rapidly growing nutraceutical industry.

Crops like dragon fruit, kiwi, and avocado are being cultivated and spread to newer areas and berries like raspberry and blueberry are finding their place in subtropical conditions. For instance, investing in developing high-yielding apple and kiwi cultivars or dragon fruit adapted to diverse agro-climatic regions across the country can reduce dependency on imports. Cocoa, coffee, and rubber cultivation are spread in the north eastern region, where the ecosystem's fragility has to be considered and careful planning is required to make the industry more sustainable and towards carbon neutrality. Crops like cashew require focused attention to avoid the heavy imports of nuts.

The spices industry has to be explored to its full extent to enhance the export earnings and be surplus in agro-commodity exports. Similarly, a residue-free spices production system has to be promoted to enhance exports. Tropical tubers like cassava, sweet potato, yams and other lesser-known tubers need to be promoted in newer pockets, and agro-based processing industries need to be strengthened. With an ever-growing population and increasing pressure on traditional agricultural systems, the mushroom industry offers a sustainable food security and income generation solution. As the horticultural sector expands, it will generate employment opportunities, particularly in rural areas, thereby contributing to poverty alleviation and economic development.

3.3. Quality planting material, rootstock breeding

To enhance horticultural crop production, improved planting stock from high-tech nurseries and hybrid vegetables should be emphasized. Tissue culture techniques in banana and pomegranate have significantly boosted production and productivity while creating employment opportunities and ensuring high-quality plants. Promoting next-generation tissue culture technology, such as a bioreactor, for higher multiplication of plants than conventional tissue culture for other horticultural crops will further assure quality production.

Rootstocks play a crucial role in addressing soil-related issues, both biotic and abiotic, while also providing suitable plant architecture. New rootstocks should mitigate soil problems and support modern production systems and mechanization, enhancing orchard efficiency. Properly selected rootstocks can modify plant architecture for optimal resource use, improve soil conditions, and enhance nutrient and water conservation. Rootstocks are now integral to the production systems of grapes, citrus, apples, and other fruit crops. Therefore, rootstock research and application should be given focused attention.

3.4. Tissue culture for the present and the future

The tissue culture industry has become a cornerstone of modern horticulture, especially for clonal and vegetatively propagated crops such as bananas, berries, tubers, and grapes. Tissue culture enables the mass production of genetically uniform, disease-free planting materials, addressing key challenges faced in conventional propagation methods, such as low multiplication rates and pathogen transmission. For instance, India produces over 30 million tissue-cultured banana plants annually, with robust growth driven by varieties like *Grand Naine*, which dominate domestic and export markets due to their uniform yield and disease resistance (Singh *et al*., 2020).

In vegetatively propagated crops, the risk of transmitting diseases such as Fusarium wilt in bananas and viral infections in berries is significantly reduced through tissue culture, as the process relies on aseptic conditions and the use of pathogen-free explants. Studies have demonstrated that tissue-cultured bananas yield 20-30% more than conventional methods due to their uniformity and enhanced stress resistance (Patil *et al.*, 2018). Similarly, grapevines propagated through tissue culture exhibit improved disease-free establishment and higher survival rates than traditional cuttings propagation. The tissue culture industry in India is projected to grow at a compound annual growth rate (CAGR) of 12.6% between 2023 and 2030, with the market size expected to exceed USD 150 million by 2030 (IBEF, 2023). However, fulfilling this demand requires technological advancements, such as bioreactor-based tissue culture systems that enhance scalability and reduce production costs. Bioreactors, such as Temporary Immersion Bioreactors (TIBs), are already being used to produce large volumes of plantlets with higher uniformity, efficiency, and cost-effectiveness.

The industry should also focus on exploring better explant sources, such as shoot tips and meristematic tissues, which have lower chances of harbouring systemic pathogens, further ensuring disease-free propagation. Research into optimized media formulations, improved somatic embryogenesis techniques, and enhanced acclimatization protocols can bolster the quality and survival of tissue-cultured plants. To meet future requirements, the tissue culture sector should scale up to produce billions of high-quality planting materials annually. This will support the growing domestic horticulture industry and position India as a global leader in the export of tissue-cultured plants. Investments in skill development, advanced R&D facilities, and policy support are essential to achieve this vision and contribute to sustainable agriculture and economic growth.

For instance, around 500 million plants are generated annually through micropropagation, with 90% belonging to ornamental varieties. The current landscape of tissue culture is characterized by advancements in micropropagation techniques, enabling the propagation of high-value crops such as orchids, gerberas, and spices. Recent innovations also include automation and bioreactor systems, which enhance scalability and reduce labor costs, making tissue culture more accessible. The future trends in tissue culture technology indicate a growing integration of advanced biotechnological tools such as genetic engineering, and bioreactor systems, which can enhance the efficiency of plant propagation. As the global demand for high-quality horticultural products rises, the emphasis on optimizing tissue culture processes, reducing production costs, and ensuring quality control becomes paramount. Researchers are focusing on developing cost-effective practices and using bioreactors to improve growth rates and reduce space and labor requirements. Moreover, the *in vitro* storage of genetic materials via cryopreservation presents a sustainable approach to preserving germplasm, offering potential solutions to the challenges posed by climate change and genetic erosion.

3.5. Grafting technology for biotic and abiotic stress mitigation in vegetables

Beyond traditional fruit grafting, vegetable grafting offers advantages over conventional growing methods. Vegetable crops often suffer yield reductions of 60-70% due to biotic factors such as soil-borne pathogens and nematodes, and abiotic factors like salinity, drought, flooding, waterlogging, heavy metal contamination, suboptimal temperatures, and nutrient deficiencies and toxicities. In recent years, the use of rootstock for managing soil-borne diseases and problematic soil for growing vegetables has been found successful. The rootstocks are helpful in melons, brinjal, and tomato for growing in problem soils.

Vegetable grafting is widely used in the Solanaceae and Cucurbitaceae families to enhance resistance to various stresses and improve plant growth and productivity. It is crucial in controlling soil-borne diseases such as *Fusarium* wilt, *Verticillium* wilt, and Root Knot Nematode. This is particularly advantageous in protected vegetable production systems, including tunnels, hydroponics, and organic farming. In addition to disease and pest resistance, grafting provides increased vigour, early production, and higher yields in certain vegetables. Various manual grafting methods are suitable for each vegetable, and recently, grafting machines have been developed to meet the high demand for grafted plants. Mini robots can also be developed to perform the grafting on succulent vegetables. Intensified research is needed to identify appropriate rootstocks in vegetables, ensuring the freedom of scions from virus diseases to enhance productivity.

3.6. Moving towards climate-smart horticulture

Embracing a sustainable development approach is vital for achieving carbon-positive farming, particularly in the face of climate change. Key strategies include harnessing renewable energy, conserving forest and water resources, and engaging in reforestation initiatives. Educational programs for growers are essential to modify existing horticultural practices and increase the adoption of greenhouse technologies. Additionally, integrating high-tech horticultural methods will play a crucial role in selecting plant species and cultivars that are resilient to climate impacts. Developing new cultivars that exhibit tolerance to high temperatures, resistance to pests and diseases, shorter growth cycles, and good yields under stress conditions is imperative for future agricultural success. Moreover, prioritizing Integrated Nutrient Management (INM) and improving planting stock quality can significantly enhance horticultural productivity while minimizing climate-related impacts. Innovative practices such as organic farming, trap cropping, and biocontrol measures should be encouraged alongside the establishment of high-tech nurseries. Intensive research into adaptive cropping schedules will be critical as technology advances enable off-season cultivation. This transition necessitates developing suitable cultivars and production technologies for industrial settings with controlled climate and lighting conditions. Furthermore, effective light manipulation techniques are essential to maximize agricultural output while optimizing input use. Incorporating Modified Integrated Pest Management (IPM) technologies is also crucial for sustainable horticulture, as it combines various pest control methods to maintain pest populations below economic injury thresholds. Transitioning from exploitative farming practices to carbon-neutral and positive methods is essential for fostering ecological sustainability and financial viability in agriculture.

In India, agriculture contributes approximately 17% of greenhouse gas emissions, a figure likely to increase with the prevalent practice of crop residue burning. To address these challenges, environmental sustainability and social responsibility should be prioritized in horticulture. This includes adopting sustainable farming practices, minimizing waste, and reducing chemical inputs to enhance the reputation of horticultural products. Organic farming, integrated pest management, water-efficient irrigation, and soil health management are vital components of a sustainable horticultural framework. Promoting biodiversity conservation, agroforestry, and climate-smart horticulture can help mitigate climate change impacts while improving resilience. Moreover, subsidized electricity for horticulture has led to the cultivation of water-intensive crops, which poses risks of declining water tables and future shortages. Despite India's relatively small share in global exports, it has emerged as the largest exporter of virtual water—water embedded in exported agricultural products. Hence, strategies should focus on enhancing agricultural production to meet dietary needs while diversifying crop varieties to improve nutritional quality. Ultimately, efficient resource management is crucial, aiming to achieve higher outputs with reduced inputs of light, energy, water, and fertilizers on increasingly constrained land. Adopting a sustainable development approach, utilizing renewable energy, conserving forests and water, and reforestation are key measures for carbon-positive farming. Educational programs for growers, modifying current horticultural practices, and increasing the use of greenhouse technology can help minimize climate change impacts. High-tech horticulture should be adopted more intensively, carefully selecting plant species and cultivars, considering climate change impacts. Developing new cultivars of horticultural crops that are tolerant to high temperatures, resistant to pests and diseases, have a short duration, and produce good yields under stress conditions will be essential. It should enhance production to meet dietary needs while enriching crop varieties with nutritional diversity. Efficient use of natural resources is crucial, aiming to produce more with less light, energy, water, and fertilizers on a shrinking land base.

3.7. Alternative production systems, vertical farming, hydro/aeroponics and peri-urban horticulture

Precision horticulture has emerged as a modern solution to enhance productivity by optimizing the use of resources through advanced tools and techniques. Despite the prevalence of resource-limited smallholder farmers, integrating technologies such as remote sensing, GIS, ICT, drones, and robotics enables precision farming, supported by skilled service providers. A new approach known as integrated water resource management focuses on land development and the management of water resources to maximize economic and social benefits without compromising sustainability. Promoting integrated water management systems is essential. Emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), and Blockchain are revolutionizing farming by enhancing predictability and precision. Big data aids in optimizing supply chain management, yield forecasting, and ensuring predictable incomes for farmers.

This approach improves soil health and water quality and contributes to environmental sustainability and food security. Moreover, incorporating biofertilizers can reduce reliance on chemical fertilizers, boost productivity, and help mitigate greenhouse gas emissions. Pollinators produce three-quarters of fruit and seed crops, including bees, bats, insects, butterflies, birds, and beetles. Unfortunately, many pollinators, especially bees, are severely declining, and threatening crops like bananas, avocados, and mangoes.

The term "alternative horticulture" refers to non-traditional horticulture methods (Magdelaine *et al*., 2019). Horticultural practices have long utilized unconventional systems, with grafting and the use of rootstocks being historical examples that have transformed fruit production. Captive production of horticultural crops refers to cultivating these crops within controlled environments such as greenhouses, polyhouses, or vertical farms, often for specific purposes or markets. This approach offers several advantages, including year-round production independent of external weather conditions, optimized resource utilization, and enhanced crop quality and yield consistency. In the context of captive production, precision horticulture technologies such as hydroponics, aeroponics, and automated climate control systems can be employed to maximize productivity and resource efficiency. Additionally, captive production facilitates customization of cultivation practices to meet specific market demands, such as organic certification or niche varieties. Moreover, captive production systems can mitigate risks associated with pests, diseases, and adverse weather events, thereby ensuring a more reliable and sustainable supply of horticultural produce. From a business perspective, captive production enables vertical integration, where companies control the entire production chain from cultivation to distribution, thereby enhancing profitability and market competitiveness. Furthermore, captive production can foster innovation in horticulture through research and development initiatives aimed at improving crop varieties, cultivation techniques, and post-harvest handling processes.

Controlled environment agriculture, such as hydroponics and aeroponics, is now changing vegetable production by allowing for soil-less cultivation and improved yields. Hydroponics, for instance, minimizes pest issues and ensures constant nutrient supply, though it can be limited by factors like carbon dioxide levels and light exposure. To further enhance yields, some greenhouses use carbon dioxide enrichment and supplementary lighting. Aeroponic technology, particularly for potato seed tubers, has proven effective, reducing agrochemical use and greenhouse gas emissions, although it involves higher costs and energy consumption. In addition to these technologies, such as precision lighting using LEDs or nanotech-based approaches, they also have a say in the next generation of horticulture.

Peri-urban horticulture, which involves growing crops around city peripheries, provides affordable fresh produce and vital nutrients to local communities. However, converting agricultural land near cities into non-arable areas poses challenges. Peri-urban systems often incorporate solid waste management, night soil, and water reuse, presenting both opportunities and challenges. The migration from rural to peri-urban areas due to increasing urbanization offers livelihood opportunities, but also risks urban poverty and food insecurity.

3.8. Plant architecture and crop regulation

'Concept of large trees' eventually became the 'concept of small trees', and higher tree numbers translated into higher yield and yield efficiency. While rootstocks and horticultural practices such as training and pruning largely dictated the last century, the focus on controlling tree architecture (Costes *et al.,* 2006) has become a genetic x management concept. Genes that can control the tree architecture have been identified in many important crops such as apples (Bai *et al.*, 2012) and grapes (Boss and Thomas, 2002; Cousins, 2012). Thus, genetics' role in plant architecture has become more apparent. However, the difference in the next generation will be more 'custom-made or architecture' tree sizes, where we will be using precise genetics to develop trees of desired stature. That brings us to another area where future horticulture will be wading into- crop regulation and automation.

Crop load is now estimated using remote sensing technologies, including artificial intelligence. For instance, 'machine vision system' or artificial eyes have been developed, and these are used to estimate the crop load, as the crop load helps the farmer to apply the right amount of input to get a successful yield. Recent advancements have improved accuracy by employing more powerful and multiple sensors to view the tree from various angles. These enhanced technologies are now also applied to crops like almonds and mangoes (Payne *et al*., 2016; Rahman *et al*., 2018). In addition to estimating crop load, these technologies can also predict harvest times (Anderson *et al*., 2021). Artificial Intelligence (AI) further enhances precision harvesting by detecting subtle colour differences that may be missed by the human eye and reducing damage that can occur with manual harvesting, such as with mushrooms.

3.9. Protected cultivation and floriculture

Various protected cultivation structures offer different ranges of temperature, humidity, and UV radiation, and their construction costs vary. These factors can lead to producing vegetables, fruits and flowers with advantages such as superior quality, higher productivity, and better market prices for growers. During dry months, intense heat and high UV radiation in open fields can degrade the quality of leafy vegetables, whereas protected structures help maintain optimal conditions for growth. Low-cost shade nets are particularly effective for high-value leafy vegetables such as coriander, spinach, fenugreek, and insect-free brinjal crops. Net houses can be utilized for the year-round cultivation of crops like capsicum, tomato, okra, cauliflower, cabbage, brinjal, beans, parthenocarpic cucumber, and other cucurbits. These structures also reduce the incidence of insect pests and diseases, resulting in lower chemical residues on produce.

India's floriculture industry is expected to experience significant growth and transformation. The sector is projected to expand at a compound annual growth rate (CAGR) of around 20%, driven by increasing domestic demand and export opportunities. India, currently the second-largest producer of flowers, could see its market size exceed $5 billion, with exports growing due to enhanced infrastructure and technological advancements. Protected cultivation offers controlled environmental conditions, allowing year-round flower production, quality enhancement, and increased yield. It also reduces dependency on seasonal variations and mitigates risks from pests and diseases. By adopting protected cultivation, India can improve the quality and quantity of its floral produce, meeting domestic and international demands. This shift is expected to bolster India's position in the global floriculture market, with an increasing share of exports and a projected market size exceeding $5 billion. Marigolds and tuberoses are traditional flowers with significant cultural importance in India. Innovations in these varieties, such as extended blooming periods and improved aesthetic qualities, could also be vital in expanding the floriculture market. These flowers have a strong demand in religious and social ceremonies, and enhancing their quality and production through protected cultivation and breeding techniques could further increase their market share domestically and in exports.

3.10. Organic horticulture and natural farming

There is a need to integrate agroecology with on-farm models of organic and natural farming, combined with *in situ* water conservation and crop residue management. The organic produce market is the fastest-growing globally, including in India. As the world's largest producer of organic products, India is poised to build a nutritionally, ecologically, and economically healthy nation by further promoting organic farming. While the per-hectare usage of agrochemicals in India remains significantly lower than in many developed nations, there is increasing awareness about their adverse impacts on human health, soil quality, the environment, and sustainability. Many countries are promoting biocontrol methods for pest and disease management to address these concerns. The Indian government has introduced various initiatives to encourage alternative production methods such as organic farming and natural farming to decrease reliance on agrochemicals.

Research in organic cultivation is crucial for addressing existing gaps and advancing sustainable practices. One significant gap is the development of precise pest and disease management strategies tailored for organic production of horticultural crops. Current methods often lack targeted solutions, leading to yield losses and reduced quality. Additionally, comprehensive studies are needed on how climate change impacts organically grown crops, including the development of resilient varieties and cultivation techniques. Optimizing nutrient management in organic orchards and fields also remains challenging, necessitating research into efficient organic fertilisers and nutrient cycling. Investigating the economic viability and scalability of organic farming, from smallholder farms to large commercial farms, is essential for broader adoption. Moreover, region-specific guidelines for organic production of crops should be developed to accommodate diverse climatic and soil conditions.

Nevertheless, agrochemicals contribute to increased productivity and protection against pests and diseases. Scientific evidence both in India and globally indicates that the absence or replacement of agrochemicals with natural and organic inputs can result in yield reductions. The food and economic crisis in Sri Lanka, which followed a 2021 ban on synthetic fertilizers and agrochemicals, highlights the importance of a careful approach to reducing agrochemical use. Balancing the need for safe, high-quality, and environmentally sustainable food with adequate food supply is challenging. Transition from conventional to organic or natural farming methods without disrupting domestic supply needs to be emphasized. Collaborative research involving academia, farmers, and industry stakeholders can address these gaps and advance organic cultivation, contributing to a more sustainable and resilient horticulture industry.

3.11. Postharvest management, supply chain management, export competitiveness and import substitution

Creating a glitch-free market capable of supplying quality products to consumers is essential for sustaining and thriving industries. The storage challenges of horticultural crops, particularly fruits and vegetables, are significant worldwide and pose a substantial economic burden in developing countries. Current storage methods are often narrow in scope, expensive, and not adequately tailored to the needs of typical fruit and vegetable growers and packers. Optimal packaging, storage, and distribution technologies are vital for perishable goods, as improper handling can result in considerable losses. This issue is especially critical in developing countries, where distribution and preservation systems remain underdeveloped.

While the export of horticultural commodities is increasing, their import is also rising. Efforts should focus on reducing imports and enhancing exports. When engaging with international regulators and buyers, showcasing adherence to quality and safety standards is critical to gaining credibility and trust. Currently, 67% of India's exporters are one-time exporters, unable to sustain regular exports due to challenges in meeting compliance standards. Buyers in Western countries increasingly demand traceability and transparency metrics to approve products. Nanotechnology offers promising solutions to reduce post-harvest losses in South Asia, especially for perishable fruits. Successful nanotechnology interventions have been reported to extend shelf life (Kutty, 2019). Future strategies may include natural products derived through 'green technologies' to address growing food and nutritional security needs.

Despite limited success in exporting products like grapes, onions, potatoes, mangoes, and bananas, emphasis on traceability, adherence to good agricultural practices (GAP), and certification procedures is vital. Educating farmers about export requirements and international quality standards is essential for improving global competitiveness. Farmers should collaborate to expand fruit-growing regions, which can lower input costs, ensure uniform plantation maintenance, and facilitate the production of export-quality produce. Such collaboration also reduces the cost of obtaining GAP certification.

Branding and quality should receive significant attention. It is crucial to identify and promote special zones for potential crops. Traceability in farm and crop management for high-quality yields, adherence to quality standards, certifications, and end-to-end traceability are essential for building confidence among buyers and consumers.

New policies aim to increase India's agricultural exports to $100 billion in the coming years while maintaining a stable trade policy regime. Government initiatives focus on pre-harvest linkages, strengthening market access, introducing new regulatory mechanisms like contract farming without compromising farmers' interests, promoting organic farming, and bridging infrastructure gaps. To achieve this, horticultural produce exports should become more competitive through the following key actions:

- Ensuring that prices in domestic markets are significantly lower than international prices.
- Reducing the price spread across various stages of marketing.
- Integrating producers into global value chains by providing better SCM and logistic solutions.

Additionally, incentivizing farmers through subsidies and financial support to adopt modern farming practices like protected cultivation, drip irrigation, and precision farming can boost domestic production. Encouraging intercropping and agroforestry systems with other compatible crops can optimize land utilization and enhance productivity, contributing to import substitution goals. Furthermore, facilitating access to credit, market linkages, and technical know-how can empower smallholder farmers to transition towards new market-driven crops. Implementing quality control measures and establishing cold chain infrastructure to ensure post-harvest management and preservation of perishable horticultural produce is essential for meeting domestic demand and competing with imported counterparts. In parallel, promoting value addition through food processing, packaging, and branding initiatives can enhance the competitiveness of domestically grown new crops in the market. Farmers' producer organizations could benefit from improved farming infrastructure, such as cableway conveyor systems and APEDA-certified pack houses with the right last-mile connectivity (APEDA, 2016). Creating product-specific export zones with tax incentives for entrepreneurs and developing exclusive railway transport systems connecting growing regions could further support the industry.

Efficient logistics and distribution systems are essential for the timely and cost-effective delivery of horticultural products to consumers. Optimizing transportation routes, ensuring proper storage and handling facilities, and minimizing product losses during transit are critical considerations in value chain management. Develop market intelligence systems, promote international collaborations, and align with global standards and certifications for export competitiveness. To achieve targeted growth, there is a need for an effective value chain, the activities starting from conceptualization till it reaches the consumers, involving all the stakeholders in the supply chain. With enhanced efficiency of links in the supply chain, there is enhanced output, which improves profitability. The value chains could be further made effective through technological integration, logistics, green corridor, priority in ports and policy supports such as trade agreements and most favored nation. It can help maintain an inclusive ecosystem where farmers, entrepreneurs and all the stakeholders benefit from employment, income, and quality produce for consumers. Understanding consumer preferences, market trends, and demand patterns helps in aligning production and marketing strategies accordingly. The traditional market system, which involves bulk selling and buying through numerous intermediaries, presents several drawbacks. As a result, there is a need to develop alternative marketing systems and options. Emerging channels such as app-based sales by farmers or farmer groups, e-commerce, and digital commerce create new marketing opportunities. These methods enable producers to reach consumers directly, enhancing their ability to capture better prices and meet specific consumer preferences and therefore need to be strengthened and regularized.

3.12. Processing, value addition, food safety to health and nutrition and promotion of secondary horticulture and circular economy

India wastes nearly 80 Mt of food at the retail and consumer levels, ranking just behind China. With climate change exacerbating extreme heat, this issue is expected to worsen in South Asia, a region particularly vulnerable to rising temperatures. In fiscal year 2020-21, India lost 1.53 trillion rupees ($18.4 billion) worth of food, with approximately a fifth of this loss attributed to spoiled fruit. Addressing food waste, especially in horticultural crops, is crucial; conserving existing produce is more cost-effective than increasing production. Currently, most governments are prioritizing strategies to minimize food waste.

Adding value to horticultural products through branding, packaging, processing, and product differentiation strategies can help capture higher margins and create a competitive advantage. Developing unique product attributes, promoting local or organic produce, and offering convenience to consumers through pre-cut or pre-packaged options are examples of value addition and differentiation. Export units in India often generate substantial rejects, which need to be managed through a sophisticated, robust internal market or by developing processing clusters. Unlike developed nations, India's food processing sector is primarily dominated by the unorganized sector, contributing over 80% of the share. There is a need to build infrastructure for healthy powders and purees that have high nutritional potential and can be used in functional food markets due to their prebiotic properties. Moving from primary processing to focus on tertiary processed products and further to secondary horticulture with health benefit orientation is a prerequisite to make the industry more sustainable. Over the past decade, the Government has focused on developing and promoting start-ups to create a better ecosystem and sustainable business models. Initiatives like "One District One Product" (ODOP) and cluster-based processing are strategic approaches to boost food processing, which has remained below 5% despite being a sunrise sector. Industrial emphasis on alternative energy-efficient food systems, protein and polysaccharide-based bio-actives, and smart delivery systems should be identified and promoted.

Disaggregated production poses challenges for processors. Emphasis should be placed on the bio-fortification of major foods and increasing dietary diversity. Efficient coordination among different stakeholders, including input suppliers, farmers, processors, and retailers, is essential for the seamless flow and timely delivery of horticultural products. Collaboration and communication across the supply chain help ensure the availability of quality inputs, optimized production practices, and timely delivery of products to consumers.

To meet changing consumption patterns and demographics, value addition through techniques like microencapsulation and extrusion is necessary. Encapsulating spice extracts or their purified compounds using micro- or nanotechnology can have applications in culinary, nutraceutical, drug, agricultural, and other fields, with improved physicochemical properties. Bioprospecting using bioinformatics tools and characterizing the therapeutic action of spices and horticultural crops and their extracts *in vivo* is required. It is essential to apply crop extracts or their purified bioactive principles in user-friendly modes for drug delivery, pesticide, and antimicrobial applications. This involves the chemical modification, synthesis, and appropriate packaging of spice-derived phytochemicals at defined dosages, ensuring optimum bioavailability, minimal toxicity or breakdown, and targeted site-specific delivery. The growth rate for spice nutraceuticals is projected at 10-12% per year (Prasath, 2021). Developing novel bio-molecules using proteomics and metabolomics as future pest management tools and creating electronic devices for monitoring the quality and adulteration of spices and other economically important crops is paramount for enhancing secondary horticulture. Spices are increasingly used as nutraceuticals, with this sector representing around 15% of India's annual spice production, estimated at 50 lakh tons.

Horticultural crops are the best-known renewable resource for novel nutraceuticals. Whether it is fruit, vegetables, herbs, spices, or aromatic plants, they are a rich source of nutraceutical phytonutrients. Several systems of Indian medicine, such as Ayurveda and Siddha medicine, have inadvertently revolved around the nutraceutical properties of horticultural crops. Despite using them for hundreds of years, many species' actual nutraceutical or medicinal compound is still unknown. New plants are frequently becoming the buzzword in the media just for their medicinal properties. For instance, noni (*Morinda citrifolia*) is a species that wasn't known much to the public till the late 1990s. However, in the last 20 years, noni juice has become a lucrative industry, with over 100 million litres consumed in the US alone. The juice is commercially available in about

80 countries (West *et al*., 2018), mainly promoted as an immunity booster among other things and has been shown to limit DNA damage due to excessive smoking (Wang, 2009; 2013). Recently, several nutraceutical phytochemicals have been identified and linked to human health. These include compounds such as anthocyanins, carotenoids, polyphenols, phytosterols, and terpenes, which provide protection from various types of ailments. Thus, plant bioactive molecules, which are beginning to blossom into a natural food industry, will be the mainstay in future, and it is not unfathomable to see that some of these phytocompounds will be used in space travel.

Consumers are becoming increasingly discerning about food quality, with a notable preference for horticultural products with specific attributes. This shift in consumer behaviour is accompanied by growing concerns regarding food safety, particularly the excessive and unsafe use of agrochemicals and hormones in crops and harmful chemical residues in food. These issues underscore the urgent need for stringent regulations to be implemented and enforced at both the production and post-harvest stages of horticultural products. Educating producers, intermediaries, and processors about safe application methods and acceptable levels of agrochemicals throughout the food system is crucial to ensure consumer safety. Moreover, there is a rising interest in the therapeutic properties of horticultural products and their role in boosting immunity and overall health. This has led to an increased demand for medicinal plants and varieties with specific health benefits, driving innovative entrepreneurs to create value chains that connect consumers directly with producers. To ensure the large-scale availability of these specialized products, it is essential to establish robust value chains supported by traceability and labelling systems. Additionally, the horticulture industry in India requires mechanization and the development of customized processing machinery to stabilise production and enhance scalability for future growth.

The potential of lignocellulosic crop biomass, especially banana and cassava, which have minimal economic value, for biofuel production through anaerobic digestion needs to be explored. The residue from anaerobic digestion serves as excellent manure, while compressed biogas (CBG) created from crop residue provides an additional income source for farmers. Crop biomass gases like carbon monoxide and nitrous oxide can be transformed into green energy, contributing to a circular economy and demonstrating the concept of waste-to-wealth. These advancements improve the economic viability of horticulture, highlighting innovative solutions to reduce environmental impact and enhance sustainability.

3.13. Therapeutic horticulture with emphasis on landscaping

The therapeutic nature of gardens was well understood, and ancient kingdoms made it a point to have an elaborate garden in many places within their kingdom. With the population exploding enormously and urbanization pushing people to live within manmade conclaves, such elaborate gardens have been relegated to a few spots. However, the importance of plants and gardens is being felt more than ever, and rooftop and city gardens are slowly returning, mainly as a therapeutic source for humans and their companion animals. Even heavily congested cities of the world like Mumbai, New York, Tokyo and Toronto are spending considerable budget on developing and maintaining urban gardens, and it is reasonable to expect that outdoor or indoor gardens will be present in every city in the coming years. In the coming years, city landscaping should find a place for trees and shrubs that offer an aesthetic and a suitable living environment, reduce pollution, and make cities livable. Horticulture students should be introduced to the design and implementation of city landscapes by bringing expertise from professionals and revising the course curriculum.

3.14. Technologies' integration and skilled human resource development

Horticulture is becoming more complex, and research demands more capital investment. Climate change, greenhouse gas emissions from horticulture, and sustainability concerns add to these challenges, highlighting the need for a strong R&D system. India should enhance its domestic horticultural research capabilities to stay competitive in the global market, which is rapidly advancing with numerous innovations.

Moving from conventional research methods and technology dissemination to path-breaking, disruptive methodologies is required to meet the pressing need. Product-centric to system-centric research reorientation is essential for effectively utilizing resources and a manifold increase in the outcome. Team and lab-oriented research programs should be initiated with proper focus and strategies. Short, medium and long-term goals should be set for the team, and continual review should be done for resource allocations and to manifest the outcome. Expertise away from the national agricultural research system has to be roped in, and different autonomous organizations should come together to work with the single objective of bringing the most effective product instead of working in isolation in bits and pieces. Also, more scientific and technical manpower should be recruited, and larger clusters should be made to develop disruptive products or processes.

By 2047, the demand for skilled labor in horticulture is projected to increase significantly, with an estimated need for an additional 50 million skilled workers. Currently, a significant portion of the horticultural workforce lacks formal training, with approximately 85% of agricultural workers in India being informal laborers who have limited access to modern agriculture education (NSSO, 2019). Addressing this requires a comprehensive overhaul of educational programs, introducing specialized horticulture courses at secondary and tertiary levels. These courses should encompass modern agricultural practices, sustainable farming methods, and the latest technological advancements, incorporating practical training modules to ensure hands-on experience.

However, India's adoption rate of advanced technologies is low, mainly due to insufficient extension services. Traditionally, state governments have transferred technology from laboratories to fields and provided advisory services to farmers. Recently, state-level extension systems have weakened significantly regarding resources and manpower. Therefore, effective mechanisms like digital technology are needed for speedy and cost-effective extension. Integrating emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), sensor utilization, and automation can enhance production efficiency, monitor crops, and optimize resources. There have been concerns about ICAR's effectiveness in expanding its role in horticulture R&D, education, and extension. India requires a dynamic and future-ready national research system for agriculture. Encouraging private sector R&D is also necessary. The country's agricultural R&D policy and system need significant changes to achieve the goals set during *Amrit Kaal*.

3.15. Robust extension linkages and public-private partnerships

To effectively reorient horticulture extension methods in India for 2047, a comprehensive and multifaceted approach is required, leveraging technology, capacity building, policy support, and community involvement. Firstly, integrating advanced technologies such as precision horticulture, drones, and IoT sensors can provide real-time data to farmers, enhancing decision-making and resource optimization. These technologies should be complemented by digital literacy programs to ensure farmers can access and utilize these tools effectively. Capacity building is crucial; thus, developing comprehensive training programs for farmers on modern horticultural practices and sustainable methods is essential. Extension workers also need continuous education and training to stay updated with the latest advancements. Policy and institutional support play a vital role, requiring government policies that incentivize innovation and sustainability in horticulture. Public-private partnerships should be fostered to drive innovation and provide farmers with access to cutting-edge technologies and resources. Improving market access and infrastructure, such as storage and transportation, can help reduce post-harvest losses and ensure fair pricing for farmers. Community involvement is also key; encouraging the formation of farmer cooperatives can enable collective bargaining and better market access. Additionally, ensuring gender inclusivity and engaging youth in horticulture through education and entrepreneurial support can make the sector more vibrant and equitable. Implementing robust monitoring and evaluation systems will allow for data-driven decisions and continuous improvement of extension services.

3.16. Frontier technologies, including mechanization

Horticulture in developing countries faces urgent challenges, including increased efficiency and productivity, improved food safety and quality, enhanced profitability, reduced vulnerability, and greater sustainability of environmental and natural resources. Frontier technologies offer significant potential for horticulture and can be categorised into five main areas: (i) biotechnology, (ii) digital technology, (iii) nanotechnology, (iv) space science and GPS tools, and (v) advanced engineering technologies, including sensors and unmanned aerial vehicles (UAVs). Innovations in these fields hold promise for transforming horticulture production and agribusiness.

Indian horticulture will likely see a significant shift towards automation and precision farming. Planting and sowing machines, equipped with AI and IoT, will enable precise seed placement and optimal spacing, enhancing crop yields and reducing waste. Sophisticated irrigation systems, such as sensor-driven drip irrigation and automated sprinklers, will ensure water is used judiciously, addressing water scarcity issues and promoting sustainable farming. Harvesting equipment capable of gentle yet efficient crop collection will minimize post-harvest losses and improve the quality of produce that reaches the markets. In greenhouses, climate control systems and automated fertigation will create ideal growing conditions, boosting productivity and enabling year-round cultivation of high-value crops. Additionally, drones and robotic systems will revolutionize pest and disease management, applying precision treatments and reducing reliance on chemical inputs.

The continued adoption of technology-driven solutions, such as IoT, AI, blockchain, and precision horticulture, is vital for improving the horticultural supply chain's productivity, resource efficiency, and traceability. Artificial intelligence (AI) and robotics have rapidly expanded in various scientific fields, particularly through integration with non-invasive imaging techniques, enhancing the efficiency of field data collection and analysis. Developing advanced remote sensing tools combined with machine learning (ML) is crucial for better crop monitoring and disease surveillance. Existing disease surveillance systems often rely on single-sensor solutions and lack the integration of multiple information sources. Monitoring large areas with UAVs poses challenges, but combining high-resolution satellite imagery with sophisticated ML models via mobile apps could provide more comprehensive health assessments for banana plants. Field phenomics tools use multiple sensors and robotics to gather phenotypic data across large-scale trials, enabling more accurate selection and improving agricultural practices when integrated with genomic data.

Digital horticulture aims to improve industrial metrics such as yield, profit and sustainability and to transform the sector's commodity trading, purchase of inputs, and traceability of products. Blockchain makes complex transactions quicker and cheaper to execute, benefiting stakeholders. Thus, digital horticulture needs focused attention. The Internet of Things (IoT) is a physical device network that collects, connects, and exchanges data. The devices measure the variability of parameters at multiple places to manage the crop effectively. The crop management is tailored to information about within-field variability in soil and/or nutrients and water. A well-architected Artificial Intelligence (AI) helps achieve higher yields while optimizing resource efficiency, thus enabling the farm to be more sustainable, viable and profitable. However, AI (Artificial Intelligence) should be integrated with IA (Information Architecture).

Adopting robots and automation processes reduces labor costs and minimizes product quality inconsistencies throughout production and postharvest stages. Mechanical harvesting is becoming more prevalent for crops such as wine grapes, tomatoes, nuts, olives, citrus, sour cherries, almonds, prunes, and walnuts. It is emerging as a new technology in India. Robots are also used in vegetable nurseries for tasks like grafting transplants, planting seeds, and planting plantlets in greenhouses or fields (Kobayashi 2005). These robots handle repetitive, labor-intensive tasks such as picking, pruning, pest and disease control, and weed management, potentially lowering production costs. Remote sensing technologies are crucial in detecting pests and diseases, monitoring plant health, assessing crop value, and optimizing the use of sprays and nutrients. Microbots could be designed for pathogen control, targeting specific viruses, fungi, or bacteria.

3.17. Focus on the Northeast region

India's Northeast (NE) region is a biodiversity-rich area, part of the Indo-Myanmar biodiversity hotspot (Myres *et al*., 2000), and one of India's four designated hotspots. The tropical and subtropical climate, combined with alluvial soil in the Brahmaputra and Barak plains and temperate climate with laterite and sandy soils in the hilly areas, supports diverse plant species. The region's dense forests, covering 67.05% of its area (Aggarwal, 2020), contribute to soil fertility by producing substantial amounts of humus. Of India's 15,000 flowering plant species, about 8,000 are found in the Northeast, along with six of the country's nine major vegetation types (Hegde, 2000).

Spices like ginger and chilli meet substantial domestic demand and have significant export potential, particularly to South and Southeast Asia (Das, 2016). Horticultural products from the Northeast received GI registration, including Arunachal orange, Khasi mandarin, Tezpur litchi, Kachai lemon, Tripura queen pineapple, Naga tree tomato, Assam Karbi Anglong ginger, Mizo chilli, and Sikkim large cardamom (Kashyap, 2015). The Northeast region serves as a gateway to Southeast Asia countries. Despite significant market potential in Bangladesh, Nepal, Bhutan, and Myanmar, the region's share in India's total horticultural exports remains minimal. However, products like Khasi mandarins, pineapples, gingers, and chillies have promising West Asian markets. The potential of the northeastern region should be explored for growing newer crops and strategic planning systems.

3.18. Focus on medicinal & aromatic plants

Over the past twenty years, there has been a significant increase in interest in traditional medicine systems, mainly due to their natural origins, non-narcotic nature, minimal side effects, accessibility, and affordability. Additionally, traditional medicines are being considered due to the limitations of conventional treatments for modern incurable diseases. India, which hosts 8% of the world's biodiversity within just 2.4% of the global land area, is home to around 45,000 plant species. Of these, approximately 15,000-20,000 are known to possess medicinal properties, with 7,000-7,500 currently utilized in the Indian System of Medicine (ISM). The preference for plant-based drugs over conventional medicines, despite the latter still containing about 25% plant-derived compounds, is growing, driven by a projected increase in the global population from 6.8 billion to 9.1 billion by 2050. The global herbal industry, valued at over US$ 60 billion, encompasses pharmaceuticals (US$ 40 billion), spices and herbs (US$ 5.9 billion), natural cosmetics (US$ 7 billion), and essential oils (US$ 4 billion). This industry is expanding at a rate of 7% annually and is expected to reach US$ 5 trillion by 2050. Essential oils from aromatic plants hold significant trade potential, as they are widely used in food flavoring, perfumery, beverages, toiletries, pharmaceuticals, and the pesticide industry. Advances in high-throughput technologies, such as bioinformatics and chemo-informatics, are instrumental in identifying potential plant sources for new therapeutics and discovering novel drugs through Quantitative Structure Activity Relationship (QSAR) studies. These technologies facilitate the analysis and integration of extensive data, providing insights from a holistic systems perspective. Bioinformatics tools are particularly valuable for pinpointing genes and pathways linked to key bioactive secondary metabolites in medicinal plants.

3.19. Government initiatives and implementation strategies

Smallholders will likely remain central to Indian horticulture for the foreseeable future. Empowering smallholders through self-help groups, farmer producer organizations (FPOs), cooperatives, and agricultural startups is crucial for improving access to credit, new knowledge, and better markets. While some smallholders are shifting to other sectors for better opportunities, others are expanding their operations by leasing land. This trend is growing in certain states, but the informal nature of the land lease market limits benefits for both lessors and lessees. States should formalize land leasing to encourage landowners to rent their land without fearing losing title or control. Government involvement and governance improvements are crucial for India to make substantial progress in the sector and to become a hub. The response time, transparency, accountability, speed and excellence in handholding need improvement. The Government has introduced various programs and schemes to strengthen the horticulture sector. There is a need for coordinated efforts along with an effective monitoring mechanism.

Some of the futuristic schemes to make *Vikshit Bharat* by 2047 are:

- Climate Resilient Horticulture Initiative
- Digital transformation/ UAV program for Horticulture
- National organic and sustainable farming mission
- Horticulture export competitiveness scheme
- Horticulture initiative for green energy/mechanization
- Leveraging horticulture in the Northeast with crops like berries, dragon fruit, and kiwi
- Postharvest innovation and technology mission

- Urban horticulture development program for high-value crops
- Special schemes for vertical farming/ microgreens/alternative farming models
- Mission for the circular economy and secondary agriculture

4. Way Forward

During *Amrit Kaal,* the Horticulture Resilience and Development Policy envisions a transformed horticulture sector that thrives despite challenges, drives economic growth, and ensures regional food security. Through collaborative efforts, innovation, and strategic implementation, the policy aims to position *Amrit Kaal* as a sustainable and resilient horticulture leader by 2047. The following points need consideration.

- Newer breeding strategies like speed breeding in select crops and effective utilization of crop wild relatives for developing climate-resilient, input-efficient varieties. There is a need to strengthen collaborative efforts to fast-track the development of drought-tolerant and disease-resistant varieties and facilitate farmer participation in varietal trials and selection processes, ensuring that local knowledge is integrated into varietal improvement efforts.
- Mapping the potential of highly productive and comparative advantage regions for introducing new and high-value crops like berries, date palm, and bioprospecting of minor and underutilized crops, such as jackfruit, Bael, and *aonla,* has to be explored.
- Establishing a Horticulture Sustainability Fund to support farmers in adopting sustainable practices. This fund could provide financial incentives for organic farming, agroforestry, water-efficient irrigation techniques, and regenerative and conservative horticulture.
- To develop region-specific best practices, climate-smart horticulture will need to be promoted through awareness campaigns and training programs, in collaboration with grassroots functionaries.
- Technological Integration through the launch of the direct-to-farm and business initiative to provide farmers with access to technology. Distribute IoT devices, weather sensors, and data analytics tools for precise resource management. Agri Tech Hubs and Technology business incubations in key regions should be established, offering training and demonstrations on precision horticulture, drone-assisted monitoring, and smart irrigation systems.

- Establishing robust horticulture education centers collaborating with agricultural universities for skill development will offer practical training in modern farming techniques, post-harvest management, and value addition. The younger generation needs to be encouraged to pursue careers in horticulture education, facilitated by providing scholarships and mentorship to aspiring horticulturists.

- Forming the dedicated core work group, comprising representatives from government agencies, research institutions, private sector stakeholders, and farmer associations, which will foster public-private partnerships to develop horticulture clusters, integrating production, processing, and marketing. This also should catalyse private investment in research and infrastructure development.

- Establish a modern cold storage and processing facility network in key horticultural hubs. These facilities will reduce post-harvest losses and improve the shelf life of produce. Upgrading rural road and transportation networks to ensure the efficient movement of horticultural products from farms to markets is also needed.

- Developing post-harvest value chains and small manufacturing facilities around farms to produce bio-based industrial products would increase income and generate employment opportunities.

- Technologies for producing bioenergy from crop and livestock biomass and waste are advancing. Efforts shall be made to use horti-residues in bio-energy and related industries.

- Creating a more robust, dynamic, real-time Digital Knowledge Repository to centralize research findings, best practices, and success stories to provide valuable resources for stakeholders. Extension services, supported by digital platforms, will enhance farmer access to real-time information and best practices, aiming to reduce post-harvest losses.

- The private sector should contribute to exploring opportunities in agribusiness, including farm mechanization, robotics, warehousing, logistics, cold chain management, food processing, and integrated value chain development. State Governments should facilitate producers' leveraging of these opportunities.

- There is a substantial shift towards bio and plant-based products, including medicines, nutraceuticals, cosmetics, and pest control solutions. This growing preference for natural products over chemicals and synthetics, including bio-control measures, needs to be explored with a focus on secondary agriculture.

- A dedicated monitoring and evaluation framework should be established to track program implementation progress, assess the adoption of sustainable practices, and evaluate technological integration and skill development. Investing in farmer training programs, extension services, agri-preneurship development, and technology transfer initiatives will empower farmers and enhance productivity.
- Horticulture markets, with their large price spreads, multiple intermediaries, and inadequate infrastructure, require significant upgrading and modernization. To improve these markets, facilities for grading, packaging, storage, and quality assessment should be established, and digital transactions and e-marketing options should be integrated. Promoting alternatives like electronic platforms, direct marketing, and contract farming is essential. Additionally, encouraging market innovations through agri-startups, farmer producer organizations (FPOs), and cooperatives can further enhance market efficiency and effectiveness.

5. Epilogue

Horticulture ensures livelihoods, food and nutrition security, environmental health, and sustainability. The pressing global challenges of climate change and degradation of natural resources highlight the need for diversification within the agricultural sector, which is increasingly impacting horticulture. While existing technologies predominantly cater to high-value, high-volume crops, there is a pressing need to focus on crops with specific value. India has implemented various technology and policy initiatives to advance horticulture in response to these evolving demands. Emphasizing conservation horticulture is vital, especially concerning managing dwindling resources such as soil, water, and labor. Enhancing productivity and fostering stronger connections among stakeholders, such as ICAR research institutions, agricultural universities, development departments, KVKs, NGOs, and farmer organizations, is essential for the effective implementation of various programs and their convergence.

Equally important is the development of human resources in the horticulture sector, given the anticipated growth in retail outlets, export opportunities, post-harvest technologies, mechanization, and custom hiring centers. Embracing advanced technologies, such as crop improvement techniques, Artificial Intelligence (AI), Machine Learning (ML), Next-Generation Sequencing, and genome editing, will open new avenues for precise cultivation and innovative crop varieties. Redefining research goals, production systems, education, and human resource development, fostering public and private sector collaboration, market intelligence and market mechanisms, is necessary to boost production, productivity, processing, and export of horticultural products. The objective is to create a horticulture sector that is productive, sustainable and resilient to meet the needs of a health-conscious population. Looking ahead, innovative horticultural systems like vertical farming, aeroponics, and fogponics, designed for extra-terrestrial environments, signal rapid advancements in the field. Despite the sector's adaptability to new technologies, significant gaps remain. Addressing these gaps requires a multi-disciplinary approach encompassing the entire value chain, from growers to consumers. This shift towards modernization will involve introducing and promoting knowledge-intensive practices, private sector investments, new producer institutions, integrated food systems, and novel linkages between producers and consumers. Updating outdated regulations and liberalizing the sector will foster a dynamic horticultural environment during the *Amrit Kaal*. These changes will depend on creating a supportive regulatory framework and encouraging responsible public and private investments in horticulture.

6. References

Aggarwal, A. (2020). Revisiting the land use assumptions in forest carbon projects through a case from India. *Journal of Environmental Management*, *267*, 110673.

Aggarwal, M. (2020). India's forest cover is rising but northeast and tribal areas lose. Mongabay India. https://india.mongabay.com/2020/01/indias-forest-cover-is-rising-but-northeast-and-tribals-lose/

Anderson, N. T., Walsh, K. B., & Wulfsohn, D. (2021). Technologies for forecasting tree fruit load and harvest timing—from ground, sky and time. *Agronomy*, *11*(7), 1409.

Anonymous. (2022). Agricultural statistics at a glance 2022. Ministry of Agriculture & Farmers Welfare, Economics and Statistics Division. https://www.desagri.gov.in/wp-content/uploads/2023/05/Agricultural-Statistics-at-a-Glance-2022.pdf

Anonymous. (2022). Horticulture statistics at a glance. Horticulture Statistics Division, Department of Agriculture, Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, New Delhi.

APEDA. 2016. The Agriculture and Processed Food product Export Development Authority. Govt. of India. http://agriexchange.apeda.gov.in/Marke t%20Profile/one/TOMATO.aspx

APEDA. (2016). Comprehensive master plan for tapping the export potentials of North Eastern states. Agricultural and Processed Food Products Export Development Authority. http://apeda.gov.in/apedawebsite/Announcements/APEDA_NER_Final_Project_Report_Compr.pdf

Bai, T., Zhu, Y., Fernández-Fernández, F., Keulemans, J., Brown, S. K., & Xu, K. (2012). Fine genetic mapping of the Co locus controlling columnar growth habit in apple. Molecular Genetics and Genomics, 287(5), 437–450. https://doi.org/10.1007/s00438-012-0691-4

Bai, Y., Dougherty, L., Li, M., Fazio, G., Cheng, L., & Xu, K. (2012). A natural mutation-led truncation in one of the two aluminum-activated malate transporter-like genes at the Ma locus is associated with low fruit acidity in apple. *Molecular genetics and genomics*, *287*, 663-678.

Boss, P. K., & Thomas, M. R. (2002). Association of dwarfism and floral induction with a grape 'green revolution' mutation. *Nature*, *416*(6883), 847-850.

Chand, R., Raju, S. S., & Pandey, L. M. (2008). Progress and potential of horticulture in India. Indian Journal of Agricultural Economics, 60(3), 299–309.

Chadipiralla, Kiranmai, et al. "Plant tissue culture and crop improvement." *Sustainable agriculture in the era of climate change* (2020): 391-412.

Chand, Ramesh. "Indian agriculture towards 2030—Need for a transformative vision." *Indian agriculture towards* 2030 (2022): 1-7.

Costes, E., Lauri, P. E., & Regnard, J. L. (2006). Analyzing fruit tree architecture: implications for tree management and fruit production. *Horticultural reviews*, *32*, 1-61.

Cousins, P. (2012). Small but mighty: 'Pixie' grapevine speeds up the pace of grape genetics research and breeding. Appellation Cornell, 1–4.

Das, K. (2016). Production conditions of spices in Northeast India: Cases of ginger and chilli (Discussion Paper No. 51). National Research Program on Plantation Development, Centre for Development Studies, Trivandrum. http://www.cds.edu

Down to Earth. (n.d.). The future of Indian agriculture. https://www.downtoearth.org.in/blog/agriculture/the-future-of-indian-agriculture-75384

Kobayashi, K. (2005). Vegetable grafting robot. Research Journal of Food and Agriculture, 28, 15–20. (In Japanese)

Kutty, V. (2019). Enhancing fruit preservation with nanotechnology. IDRC. https://www.idrc.ca/en/research-in-action/enhancing-fruit-preservation-nanotechnology

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity 'hotspots' for conservation priorities. Nature, 403(6772), 853–858. https://doi.org/10.1038/35002501

Nabi, T., & Bagalkoti, S. T. (2017). Growth trends of horticulture crops in India. International Journal of Multidisciplinary Research and Development, 3(3), 158–164.

Patel, V. B., & Tripathi. (2023). Scenario of horticulture research and development in India and North Eastern India. Indian Horticulture, 68(6), 6–10.

Pawar, P., & Sakhale, B. (2022). Cascading impacts of change in carbon dioxide concentration, temperature and precipitation on horticulture crops: A review. Agricultural Reviews. https://doi.org/10.18805/ag.R-2579

Payne, A. B., Walsh, K. B., & Subedi, P. P. (2014, August). Automating mango crop yield estimation. In *XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014): 1130* (pp. 581-588).

Rahman, M. M., Robson, A., & Bristow, M. (2018). Exploring the potential of high-resolution WorldView-3 imagery for estimating yield of mango. Remote Sensing, 10(12), 1866. https://doi.org/10.3390/rs10121866

Sangita Das, S. D., Ranjan Das, R. D., Hemendra Choudhury, H. C., & Ananta Saikia, A. S. (2016). Interactive effect of elevated carbondioxide and high temperature on quality of hot chilli (Capsicum chinense Jacq.).

Singh, Avinash Kumar, Aarti Sharma, Chhavi, and Akanksha Singh. 2023. "Use of Tissue Culture for Propagation of Banana Variety

Grand Naine (Musa Acuminata)". *Current Journal of Applied Science and Technology* 42 (43):1-6. https://doi.org/10.9734/cjast/2023/v42i434273.

Ud Din, M. A., & Haseen, S. (2024). Impact of climate change on Indian agriculture: New evidence from the autoregressive distributed lag approach. Asia-Pacific Journal of Regional Science, 8, 377–394. https://doi.org/10.1007/s41685-023-00327-1

Varghese, N. (2024). Extent and spread of malnutrition among children under five in Indian states. GeoJournal, 89, 49. https://doi.org/10.1007/s10708-024-11050-5

Wang, C., Jurk, D., Maddick, M., Nelson, G., Martin-Ruiz, C., & Von Zglinicki, T. (2009). DNA damage response and cellular senescence in tissues of aging mice. *Aging cell*, *8*(3), 311-323.

West, B. J., Deng, S., Isami, F., Uwaya, A., & Jensen, C. J. (2018). The potential health benefits of noni juice: A review of human intervention studies. Foods, 7(4), 58. https://doi.org/10.3390/foods7040058

4 Livestock Sector[1]

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1. Context

India's livestock sector presents a mixed picture with significant achievements and notable challenges. The greater potential of livestock sector in agriculture's growth story is evident from the fact that while value of agriculture output as a percentage of gross value remained around 18% between 2011-12 and 2022-23, the contribution of livestock to gross value increased from 4.0% to 5.5% furthermore, the share of livestock within agriculture increased from 22 to 30% during corresponding period. Milk was the largest contributor, being around 67%. Despite being the world's largest milk producer, India's contribution to global dairy exports has been negligible. It focuses on skim milk powder, butter, and fats. In recent years, however, diversification has been observed with a rise in cheese exports. Buffalo meat has dominated the exports, contributing over 79.52% of total livestock exports in 2021-22. However, sustaining and increasing these exports will require emphasis on food safety measures, value added and processed products, new markets, disease management, robust supply chains, implementing traceability and bio-security, and centralized processing facilities.

An increase in livestock numbers (from 501 million in 2012 to a projected 921 million in 2047), especially cattle (from 191 million in 2012 to 370 million by 2047) and the current shortage of feeds (44%) and fodder (36%) are major challenges. A livestock population increase of around

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84% over the next 28 years is just not economically sustainable and productive enough to meet the anticipated targets. Addressing perceived and recorded production constraints like feeding, breeding, health, and management issues is crucial. Among the factors affecting productivity, feed and fodder deficiency contributes 50.2%, followed by breeding and reproduction problems (21.1%), diseases (17.9%), and management issues (10.5%). While several attempts are in progress to mitigate these challenges, deployment of already unfolded and 'to be unfolded' frontier technologies through an appropriate technology-policy nexus will be crucial in achieving the mission *Amrit Kaal* concerning the livestock and poultry sector.

2. Major Interventions Required

- Mass production and utilization of sex-sorted high genetic merit semen will cover up to 75% of breedable cattle and buffaloes by 2047; integrate available breeding and reproductive technologies to produce and multiply high genetic merit males and females for breed improvement programs.
- Development, conservation, and utilization of Indigenous/local breeds of different species for food, income, health, and environmental sustainability while supporting the organic and natural farming drive through their bio-wastes and conversion of animal wastes into energy. A prudent plan to utilize the sizeable number of unproductive animals would also be as important as managing the productive animals with finite resources.
- Containing and managing methane emissions from enteric fermentation to achieve a cleaner climate by mitigating greenhouse gas (GHG) in a mission mode with a multi-stakeholder partnership.
- Fine-tune the technology to enhance nutrient bioavailability in scarce feed and fodder resources, resulting in higher production and productivity.
- Mission mode technology – policy action on propagating hydroponics and other modes of fodder production, including floating fodder on the water resources in wet lands, including the Ramsar sites.
- Further scaling up of the already developed animal disease diagnostics and vaccines while simultaneously working on newer tools and techniques, products and processes for emerging, re-emerging and trans-boundary diseases, preferably in a network mode with a

special focus on gene therapy for better management and control of livestock diseases.

- To achieve the 'One Health' target, contain/manage zoonotic diseases and ensure an effective public health system.
- Prepare to embrace Artificial Intelligence technology (Machine Learning, Satellite Imagery, Internet of Things, data and sensor-backed health and production monitoring, etc.), including blockchain technology for the traceability of animals/ birds and their products. Initiate collaborative research on robotics for farm operations, data storage, market trend monitoring, etc.
- Another important area is precision livestock farming models that judiciously use scarce resources like water, feed, etc.
- Create globally competitive academic institutions to produce technically competent self-, science, society, and industry-ready human resources to fill the talent vacuum in the emerging veterinary and animal sciences areas.

3. Vision and Mission

Vision: Transform the Agri-food System from plant-based food to animal-based food.

Mission: Position India's Livestock and Poultry sector as an Animal Source Food (ASF), Technology and Business hub empowering and facilitating institutions - stakeholders capacity and skills, ensuring 'Ease of Doing Livestock Centric Business' so as to contribute substantially to the ASF basket for food security, global trade and commerce and thus be an important partner in achieving the Country's domestic and global goals during *Amrit Kaal*; and ensuring livestock and poultry as important drivers of economic growth.

4. Priority Areas

4.1. Breeding and reproduction

It is paradoxical that although India ranks first in milk production, third in egg production and fifth in broiler production and houses around 54% of the world's buffalo population, yet per animal productivity remains much lower. For example, the annual average productivity of Indian cattle was 1777 kg compared to the global average of 2699 kg (2019-20). The target during *Amrit Kaal* will therefore be not only to equate this productivity with the global average but to surpass that yield, as we need a growth of around 205% in the livestock sector, encompassing all the animals that provide food of animal origin. This seems achievable considering India recorded a substantial increase of 16.74% growth between 2014-15 and 2021-22. Thanks to the Government of India (GoI) schemes, like *Rashtriya Gokul* Mission, around 981 lakhs of Artificial Inseminations (AI) were carried out across all States in 2021-22. Besides, the country was able to produce around 30.31 lakh doses of sex-sorted semen from only five semen stations. Another 33.05 lakh doses of sex-sorted semen were reported to have been produced by milk federations, NGOs, and private semen stations. This capacity has now to be tripled in the coming years, with every state of the country having at least 2–3 such semen stations, each station having a target of around 5 lakh doses of such semen. Policy funding support shall be needed to increase the capacity for *In Vitro* Fertilization(IVF), stem cell, and cloning technology implementation. While doing this, we should not lose sight of the need for a pipeline of elite animal germplasm as a source for semen or embryos.

A pragmatic approach will continuously produce elite germplasm to elevate productivity. It is heartening to note that the National Dairy Development Board (NDDB), after assessing around 25,000 indigenous animals and 8000 buffaloes, has launched the INDUSCHIP and BUFFCHIP for cattle and buffaloes - a chip specifically designed to select superior animals through genotyping/ genomic selection to identify animals with high genetic merit at a younger age – thus reducing the gestation period for production of superior animals using traditional methods. Mass production and use of such chips, together with the development of such novel tools and techniques, shall pave the way towards enhancing the productivity of our livestock. Together with these unfolded technologies, the application of genome editing technologies like CRISPR/Cas for producing elite individuals is awaited. Similarly, the use of Stem Cell technology, particularly to reinvent superior breeding efficiency in the stray males, through epididymal manipulation, is expected to be an option in the coming decades to follow for genetic improvement of milch and other animals. Additionally, fourth-generation reproductive biotechnology will be necessary to improve the reproductive health of the animals.

4.2. Feeding and nutrition

Feeding and nutrition are the key to realizing near-potential productivity growth from the methodologically bred and developed livestock population. Unfortunately, despite decades-long research and technological advancements, this aspect of livestock production has remained a cause of concern. It is, of course, not an easy task to feed an ever-growing livestock and poultry population. However, given the fact that the country has attained food security for its human population, time is not far off to achieve animal feed security provided a national program is launched like National Animal Feed and Fodder Security Mission to meet the deficit in green fodder (35.6%), dry crop residues (10.95%), and concentrate feed ingredients (44%). Unless effectively and scientifically addressed, this deficiency is likely to increase. Based on compound annual growth rate (CAGR) of livestock population between 2012 and 2019 (3.54% for cattle and 0.85% for buffalo), projected population of cattle by 2047 is likely to be a whooping 369.44 million (from 193.46 million in 2019) and that of buffalo 139.83 million (from 109.85 million). While the buffalo population will be manageable, the cattle population, in all likelihood, shall not. Therefore, the target should be to restrict the cattle population to 260 million, projected for 2035. It is estimated that approximately 500 million animals in the country are without adequate feed and fodder security, which cannot achieve the optimum productivity level. There are questions of forage crop seed availability (presently around 15-20%), grazing lands, forage production plans in the existing cropping system, crop breeding for high-quality forage together with grains, crop residue management, etc. All of these should be addressed through the National Feed and Fodder Security Mission.

Research on microbial requirements for animal growth and metabolism, their link with gut molecules, fermentation energy and overall energy transactions in the gut will be essential. Scaled-up research on meta-analysis of rumen micro flora to identify fibre/cellulose degrading bacteria/ fungi, etc., will be needed to improve nutrient availability, optimize digestion and reduce methane emission. Balancing of nutrients per production performance is crucial to saving resources and energy. In fact, the future of animal feeding will depend on the development of precision feeding protocols and the exploration of newer feed sources like insects to meet protein needs.

Lot of research has already been undertaken to find location specific livestock feeding system but could not be adopted by the farmers due to two reasons – one, the location specific feed resource is available in a limitedquantity, many a times, even to prepare a ton of feed with its incorporation and the second, there has not been any attempt to increase acreage for the identified crops. Therefore, more concentration will be required for technological support to commercially produce animal feed and mass adoption of methods like hydroponics/ aeroponics modes (with precision and quality testing) of fodder production at the household and commercial farm level. Research on bio-fortified feed and fodder, primarily to address hidden hunger, will be yet another area to focus on. Redressal of this issue shall also demand effective collaboration with institutions like ICAR-Indian Grassland and Fodder Research Institute (IGFRI), National Institute of Animal Nutrition and Physiology (NIANP, All India Coordinated Project on forage crops, and with the Ministry of Environment and Forests, and other such institutions. Global collaboration with institutions like the Food and Agriculture Organization (FAO), Rome, should also be very much on the agenda, as India is a partner with FAO in animal genetic resource conservation and utilization for food and agriculture. Funding support from GoI schemes like National Livestock Mission and Animal Husbandry Infrastructure Development Fund may be explored by inviting their participation in the program.

4.3. Health and welfare

Application of innovative diagnostic tools and techniques, methods and methodologies, processes and procedures is vital for the detection of animal pathogens at an early stage so that it does not lead to epidemic or pandemic outbreaks, negatively impact animal and human health and farmers' economy. Research in these areas is already in progress. It is a matter of pride that after successfully using the Polymerase Chain Reaction (PCR) and ELISA technologies for detection of animal diseases, several serological and molecular technologies like lateral flow assays, biosensors, loop-mediated isothermal amplification, polymerase chain amplification, and molecular platforms for field-level detection of animal pathogens have been developed to achieve higher sensitivity and point-of-care (PoC) detection of animal pathogens. Furthermore, animal disease diagnostics need to be updated regularly to capture new, emerging and divergent infectious pathogens, and biotechnological innovations are helpful in fulfilling the rising demand for such diagnostics for the welfare of society. Accordingly, in order to achieve the research goal of developing PoC diagnostics and vaccines, there is a need to develop and deploy large-scale genome resources like reference genomes, pangenomes, genetic markers, candidate genes, superior haplotypes, genotyping platforms, molecular diagnosis, gene editing, functional genomics, bioinformatics tools and technologies. It is well recognised that the CRISPR/CAS9 genome editing technology can be successfully deployed for the genetic editing of single or multiple gene targets in several animals. This new technology is efficacious for generating mutations to encode a protein that represses animal defense, say against classical swine fever. This modification has been reported to have conferred resistance to the pathogen, demonstrating that CRISPR/CAS editing can be successfully employed in engineering durable resistance, even at different levels of ploidy. However, despite these excellent scientific developments in the animal health sector, the country witnessed many disease outbreaks in the last three years, costing the nation around Rs. 50,000 crores. The irony is that the means (diagnostics and vaccines) exist to prevent this loss due to diseases (like Foot and Mouth Disease, Classical Swine Fever, Haemorrhagic Septicaemia, Peste des Petits Ruminants and Brucellosis). Still, the sector is yet to scale up diagnostic and vaccine production capacities and their timely delivery, together with capacity building of the field veterinarians on their efficacious use.

Controlling and managing zoonotic diseases to achieve the 'One Health' goal will be very important in the coming years. Search for animal disease resistance conferring genes in the 'over and underground' biota, including those in the rumen, shall have to be a focused area of research under overall microbiome research. Similarly, identifying disease-resistant genes in wild relatives (wild pig, fowl, etc) through a challenge study will be an interesting area of research. Each animal science institute/ college/ university of the country having adequate strength to pursue 21st century animal health research, may initiate novel research program on animal health in a team mode with development departments under the GoI scheme like Livestock Health & Disease Control Program (LHDCP), Animal Health System Support for One Health (AHSSOH) and the Animal Pandemic Preparedness Initiative (APPI). The overall target by 2047 should be to have animal disease threat countering technologies and packages for safer food, environment and human-animal-soil health continuum.

4.4. Animal food value chain and resource/climate management

The perishable nature of food of animal origin demands quick processing and marketing, which unfortunately are handled mainly by the unorganized sector. The post-harvest losses, which vary from 1% in milk to 7.2% for eggs, should be addressed with matching post-harvest handling technologies to minimize the loss. The way gene silencing technology is being pursued in agriculture, for example, to silence the expression of ripening genes to delay ripening, and in animal science, such technologies will have to be developed to increase the shelf life of animal products. There is a need to strengthen the value chain to improve efficiency and profitability. One important area for value chain strengthening will be to increase the percentage of organized players in the processing and marketing of animal products, which presently holds only around 31% of the market share. Considering these requirements, GoI launched the Animal Husbandry Infrastructure Development Fundto support projects on establishing dairy and meat processing and value addition infrastructure, breed improvement and multiplication farms, animal waste management for wealth creation, and veterinary vaccine and drug production facilities. The Milk Producer Companies (MPCs) and the three-tier cooperative system are key components in promoting the value chain. However, policy support for promoting organized marketing channels, strengthening cooperatives, and supporting small-scale producers will be required to reduce post-harvest losses and enhance the efficiency and quality of the products.

While working on food value chain improvement, it will be desirable to improve the resource use efficiency in animal agriculture and thus reduce the pressure on environmental degradation. One such issue is the water and methane footprint in livestock farming. On water footprint, a study by the National Dairy Development Board (NDDB) in Gujarat revealed that the average water footprint per ton of milk was 1,970 m^3 for indigenous and cross-bred cows and 1,820 m^3 for buffaloes (NDDB 2018, 2023). This footprint can be reduced by 14-20% through effective water use, installing farm automation devices in large farms, and feeding balanced rations to animals. However, time will demand that animal farms' water footprint be further assessed and mapped in line with carbon footprints. The principle of 'crop per drop' will also have to be followed in the milk and meat sectors.

Insofar as the livestock sector's greenhouse gas (GHG) emissions are concerned, it has been reported that the sector accounts for 54.6% of agricultural GHG emissions, particularly due to enteric fermentation. Since India has committed to reducing its GHG emissions by 33-35% by 2030 compared to 2005 levels, it will be the responsibility of all stakeholders to work in this direction. Including products like *Harit Dhara,* developed by ICAR-NIANP, which reduces methane emission by 14-20 percent. The diet of animals is expected to cut down methane emission to that level. The ration balancing program of the GoI is reported to have been able to cut down GHG emissions by around 13.7%. Pending the development of other such technologies, resorting to the above two technologies is expected to bring down GHG emissions by livestock to around 30% as targeted by the Government.

5. Bridging the Limitations

- Limited R&D funding to pursue innovative 21stcentury livestock and poultry research, demonstrate and showcase the technology for mass adoption and production enhancement, has been a laggard syndrome in achieving optimized growth and productivity.

- Public–public, public–private, and Public-Private-Farmer partnerships have not been taken up on a strong footing, missing thereby the combined power of policy-finance-technology-extension-backed livestock technology dissemination and skill injection to a desired level.
- Targeted planning for productivity-increasing quality inputs (such as animal seeds, feed and fodder, climate-matching housing designs, vaccines, and diagnostics) has yet to be implemented, as is being done for *rabi* and *kharif* crop planning in agriculture.
- Animal insurance and credit require policy support and reforms.

6. Priority Areas

6.1. Milk sector

The current milk production is 230 Mt, and the demand by 2047-48 under the Business-as-Usual (BAU) and High-Income Growth (HIG) scenarios will be 480 and 550 Mt, respectively (NITI Aayog Working Group on Crop Husbandry, Agricultural Inputs and Demand-Supply Report, 2024). The following actions are envisioned to achieve the targeted milk production.

- Industrialisation of dairy farming will ensure efficient utilization of limited resources, aiming for profit optimization, sustainability, and safeguarding the environment.
- The proportion of unproductive females will increase significantly, calling for effective culling policies.
- More attention would be needed for optimum use of assisted reproductive techniques, including sex sorted semen stations, bull mother farms to produce around 40 million additional females and integrate embryo transfer technology at the field level for the production of both elite males and females.
- Launching of an animal feed and fodder mission targeting the Himalayan region and marginal lands for fodder trade, as is done in other food commodities from plenty to scanty regions. Make the hydroponics and aeroponics mode of fodder production science user-friendly.
- Creating designated institutes nationwide to produce animal disease diagnostics and vaccines, and strengthen service delivery. Creating facilities for targeting disease-resistant genes from bioresources like bacteria, fungi, insects, etc., for gene-based control of important diseases. Issues of AMR, which are gaining importance, also need to be integrated into health management protocols.

- Milk value chain facilities should be strengthened and expanded to ensure the cost-effectiveness, quality, and safety of milk and milk products. Byproduct utilization (dairy and animal waste) would have to be integrated into the production system to maintain the environment and improve the economics of dairy farming.
- Appropriate management technology needs to ameliorate the environmental costs of milk production and processing in terms of its water footprint (WF) and carbon footprint (CF) from production, processing, and delivery.
- Species-specific milk collection, processing, and brand promotion should be encouraged to exploit their specialty and functionality for niche area markets, both domestic and export, adhering to FSSAI standards.
- Components of insurance and credit should become part of the future policy.

6.1.1. Strategy and action plan

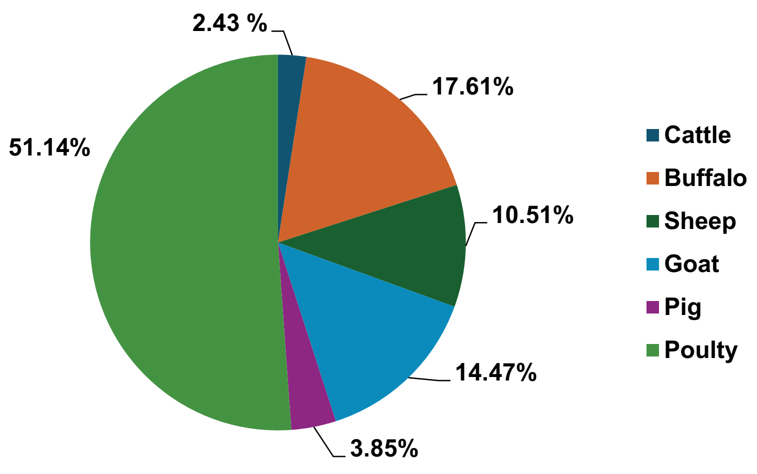
- Launch barcoding/ unique identification numbers for all animals and prepare animal AADHAR cards nationwide. Establish reference population with the available data on dairy animals and optimize the phenomics and genomic selection methods (Phytotron facility for animals) to develop dairy animals with higher productivity, efficient reproduction, disease resistance and climate-neutral attributes.
- Develop completely indigenous technology for the sexing of semen so that it can be easily integrated into the semen stations.
- Implement methane reduction technologies in dairy farms while using advanced research for novel technologies.
- Partner with the Natural Farming/ Organic Farming Mission for fodder production and establish fodder banks in every village.
- Initiate efficiency management protocols for already developed Pen-side diagnostics and combo-vaccines, and continue the development of time-matched ones.
- Develop models for a circular economy (dung for fuel and slurry; urine for biopesticides, etc.) and popularise ICT tools for farmer advisories.
- Implement precision livestock farming tools both in small and large dairy production systems.

- Complete maintenance of the cold chain from points of production to delivery using smart packaging systems.
- Initiate focused research on non-bovine milk to benefit from species-specific milk and their products in designer milk with nutraceutical properties.
- Develop dairy animals as bioreactors for the production of therapeutic proteins for the pharmaceutical industry.
- Utilize major and medium dairy farms to capture solar energy as a third crop for additional income.
- Enhance exports of the best germplasm (semen) developed in India and milk and milk products.
- Point-of-care testing tools for milk and milk products in open markets.
- Establish global dairy centers in India and abroad.

6.2. Meat sector

India is producing 9.77 Mt of total meat annually (DAHDF, 2023) through 88 Agricultural and Processed Food Products Export Development Authority (APEDA) approved units, 892 state-registered, and 4000 licensed slaughter houses, in addition to more than 20,000 unregistered slaughter units. These units slaughter approximately 220 million livestock and 3316 million poultry birds annually. Share of meat from different species is projected below (Figure 1):

Figure 1. *Species-wise distribution of meat production (2023)*



Source: *BAHS, DADF, 2023*

By 2047-48, demand for meat is estimated at 21 Mt under the BAU scenario and between 21-25 Mt under the HIG scenario (NITI Aayog, 2024). Further, considering the meat export, the production is targeted at 30 Mt. Given the production of 9.77 Mt, the sector has to grow 2.5 to 3 times to meet the demand for meat by 2047. The meat sector is projected to grow at 3.61 and 4.71% per annum under BAU and HYG scenarios, respectively, against the targeted demand of 4.48 and 5.59%. The value addition, presently below 10% for the food sector, is projected to reach around 30%, which can further increase demand for fresh meat (CII Food Processing Vision 2047). The NITI Aayog estimates that approximately 80% of the export potential of bovine meat has been harnessed, and its production is likely to remain between 1.0 and 1.5 Mt by 2047.

India is currently exporting meat and meat products valued at Rs. 33,280 crores (DGCIS, 2023-24), of which 93% is contributed by carabeef. India exported 1.29 MT (75% of the total produced) deboned frozen carabeef worth Rs 31,010 crores to 36 countries in 2023-24 (APEDA, 2024). Though around 16% of total meat produced is processed, only 3% of it is processed into value-added products as against 75% in Russia, the USA and the EU. Envisioning a scenario of an extremely busy working-class population as the years roll by, the demand for processed and value-added meat is likely to be more than double from the present figure of 16 and 3%, respectively, for which provisioning of needed infrastructure and facilities will be required.

6.2.1. Strategy and action plan towards a pink revolution

- Considering the projected population growth of large ruminants at one% only, the meat sector is envisioned to be dominated by poultry meat, raising its contribution from the present level of 51 to around 61% by 2047. Similarly, contributions from small ruminants and pigs are also to be enhanced by around 2.5 and 1.0%, respectively.
- Though slaughter policy is a state subject, there is an urgent need to have a uniform slaughter policy throughout India with clear guidelines for various species.
- Establishment of advanced/automated slaughter houses, one each in the capital cities for large animal and portable/mini slaughter houses for small ruminants, pig and poultry with proper cold chain/refrigerated truck facilities.

- Framing and implementing schemes for male buffalo calves, broiler sheep, and goats to boost total meat production in India. The scheme may also cover private players and NGOs.
- Indian ethnic meat and its products are of special significance, and it is envisioned that they will be promoted in the national and international markets.
- Development of shelf-stable products/modified atmosphere packaging, including nano-packaging technologies for retaining the quality over long-distance transportation and storage
- Novel meat products like carabeef and other protein/energy bars (like chocolate bars) are envisioned to be highly sought-after value-added meat products.
- A detailed study on synthetic meat should arrive at a futuristic demand-consumption scenario and draw an action plan accordingly.
- Development of molecular kits to diagnose stale meats/meats from different species and sexes, as well as bacterial/parasitic loads at retailers and the field level.
- Formulation of guidelines for meat-water-energy synergy for environmental sustainability and resilience.

6.3. Egg sector

The egg sector in the country has witnessed a remarkable growth of 7.9% in recent times, with the production of 138.38 billion eggs, making 101 eggs available per person per annum. This availability has to be increased to 180 eggs (WHO recommendation), covering an additional anticipated population of 220 million by 2047. The NITI Aayog estimated a requirement of 18-21 Mt of eggs under a high-income growth scenario, or about 210 billion numbers. For this, the country has to have the following targets (Table 1):

Table 1. Projected target (Mt)

Current at 2023	2030	2040	2047
13.8	16.0	18.5	21.0

Out of the total eggs produced, the contribution from the commercial sector is around 79-80%, and the remaining 20% is from the Backyard system. Both these sectors might face two challenges in egg production in the foreseeable future: (1) the commercial sector problem will be keeping the production cost at a sustained level countering the high price for feed ingredients like soya etc., and (2) the Backyard system might suffer if the food subsidy to the households is withdrawn as part of this food is fed to the rural poultry. While the commercial sector shall have its R&D agenda in addition to accessing technologies from public and private institutions from home and abroad, it is the backyard system pursued by public sector institutions and small and marginal farmers, the product of which is also preferred by the consumers, that needs visionary support.

In fact, its contribution to the egg sector has to be enhanced from 20 to at least 30%, or a contribution of 6.30 Mt of eggs out of the targeted 21.0 Mt. Currently, the contribution of rural poultry eggs is 12% (16.60 billion) of the total production of 138.38 billion numbers (DPR, Hyderabad communication). This contribution is envisioned to be raised from 12 to 20% (42 billion) of 210 billion eggs by 2047.

6.3.1. Support needs to achieve the targets

- A nationwide program on rural poultry (chicken, duck, quail etc.) jointly by ICAR poultry institutes, State Veterinary Universities and Veterinary Colleges under State Agricultural Universities and the farmers' bodies encompassing breeding and other managemental aspects to produce rural layer strains (not dual purpose) with minimum egg laying capacity of 180-200 eggs each using Marker Assisted and Genome Editing technologies. Need-based financial and training support to each institute shall be necessary.
- While developing such strains/breeds, focus should be given on the competitive advantages of rural poultry egg consumption, such as yellow yolk/ organic production mode, nutritive/ bio-fortification values, and being free from antimicrobial residue effects. As the demand for nutri-rich eggs will triple over time, production technology for designer eggs with omega-3 fatty acid content and other nutraceutical properties will be further fine-tuned and made available. Financial support for establishing multi-locational poultry seed production of the developed or improved varieties in partnership shall be needed.
- With the present thrust on Natural Farming, a special multi-stakeholder partnership drive to introduce rural poultry in such areas will be desirable. Additionally, natural duck farming for eggs along major water bodies like reservoirs, lakes, Ramsar sites, and watershed areas, particularly in regions like the North East, will fuel the national egg basket.

- To perform optimally, rural poultry will also need additional feed supplements like maize and soybean, which are produced organically. AICRP's reach on these crops to rural poultry-concentrated villages/ natural farming areas should be facilitated.
- Some rural poultry, specifically the Red Jungle Fowl, are believed to carry resistant genes against some of the dreaded poultry diseases, like Avian Influenza. This belief has to be researched through challenge studies under a controlled bio-security set-up or on an uninhabited island to see if any resistant line is found. If yes, mining/ unearthing the resistance-conferring gene will compensate for all the investment in the poultry sector.
- Notwithstanding issues like DIVA, vaccines against diseases like bird flu and other emerging/ reemerging diseases should be attempted.
- Develop appropriate linkage from the breed and technology developer to the farmers, retailers, and consumers chain, bringing it online and offline and using e-NAM marketing.
- Post-harvest losses for eggs are reported to be around 7.5%. This the case of rural poultry eggs, where proper packaging and transportation technologies are not applied, can be this loss brought down to around 2-3% with improved packaging and transportation means.

6.3.2. Strategy and action plan

- Performance validation and technology gap filling of the developed breeds at different locations in a partnership or network mode with line departments/ KVKs under various central schemes.
- Assessment of nutritional/ health and economic benefits to the farm families and impact assessment of rural poultry on the national egg basket.
- Development of rural poultry feed formulation in line with commercial feeds using regionally available feed ingredients produced under natural/ organic farming, together with mass production of identified feed for computation of a suitable ration.
- Development of health and parasite management package of practices.
- Start-up promotion for backwards and forward support and MSME projects on poultry byproduct utilization and value addition to eggs.

- Address the issue of regional imbalance in the per-person availability of eggs.
- Molecular kits for disease diagnosis and vaccines against highly contagious poultry diseases like avian Influenza, with strict monitoring of the potency of already available vaccines.
- Facilitate egg farmer producer companies to leverage the benefit.
- Enter into global egg markets with specially designed eggs produced.
- Develop kits to diagnose synthetic eggs for human health security.
- Work on the sustainability parameters once the target is achieved.
- Design economically suitable and bio-energy propelled small egg hatcheries for rural farmers.
- Develop waste handling technologies for feathers from spent hens/ culled males and other offal, including the important proteins for multifarious uses.

6.3.3. Technology platform

Five technology platforms across the country are envisioned for the commercial poultry, which is expected to be 100% technology-driven with all forms of OMICs and Artificial Intelligence technologies. These platforms shall also work on using robots in areas like circular economy, converting waste to wealth, and precision feeding and management technologies. Since data will play a crucial role in designing and applying all forms of AI, including Blockchain technology, machine-operated data repository creation is envisioned. Together with these, nanoscience, may be in combination with genome-edited technologies, will have to be applied in developing a newer type of high-performing layer breeds with an average egg production capacity of 320 eggs. The technology platform will also have to be used for identifying disease-resistant poultry lines, if any.

(i) Wool and fiber

India, with 74 million sheep and 1 million fiber producing goats (Gaddi, Changthangi breeds) is the ninth-largest wool/fiber producer in the world with annual production of 33.61 million kg. The major share is Carpet Grade (85%) whereas Coarser and apparel Grade is 10% and 5%, respectively. Total fine ($<25\mu$) wool production is around 2 million kg and Pashmina/Cashmere goat fibre accounts for 50,000 kg/annum. The species-wise contribution by Ram/Wether, Ewe and Lamb in the total wool production during the year 2022-23 was 72.17%, 13.92% and 13.91%, respectively. Pastoralists contribute almost 65% of the total wool production. The five major wool-producing states in the year 2022-23 were, Rajasthan (47.98%), Jammu and Kashmir (22.55%), Gujarat (6.01%), Maharashtra (4.73%), Himachal Pradesh (4.27%). Gaddi sheep and Chegu and Changthangi goats produce fine wool with an average yield of 1.25 kg/annum whereas Magra, Chokla, and Marwari breeds produce medium wool with average yield 0.9kg/annum; these figures have remained almost constant since 2003. Majority of the coarse wool is produced from mutton producing sheep breeds. For mutton and carpet wool sheep, mutton constitutes 70-75% of the value, carpet wool 15-18%, and the rest comes from skin, hides, and manure. In contrast, for fine wool-producing sheep and goats, wool represents 70%, meat 20%, and skin, hides, and manure 10%.

The growing populations of sheep and goats contrast sharply with the ongoing decline in wool production, which has dropped by more than 25% over the past decade, from 50.5 million kg in 2002 to just 33.6 million kg in 2022. This trend is further highlighted by the significant decrease in the number of rams and wethers shorn, plummeting from 48.3 million in 2016 to only 22.4 million in 2022-23. These figures clearly indicate a shift in the industry's focus, with sheep increasingly being utilized for meat production rather than wool. Additionally, the practice of early slaughter, often at just 5-7 months of age, underscores this transition. Low demand of wool, low wool yield / sheep, low wool prices, competition from synthetic fibres, reducing grazing lands, adverse weather conditions, tropical geography, and preference for imported wool are some other limiting factors. These would also affect the future employment potential of Indian wool industry which currently provides employment to around 1.2 million people in the organized sector, around 2 million in associated industries and around 0.3 million in the business of carpet weaving.

In 2022-23, India's wool sector was valued at $1.69 billion, with 5.43% growth in exports of ethical and traditional products like Kullu shawls and Kashmiri scarves over the past decade. Woolen carpets accounted for 80% of the country's woolen exports. High-quality pashmina products are increasingly threatened by counterfeits, which undermine their reputation and sales, leading international buyers to demand full traceability of the wool value chain. Current government initiatives are not enough to address wool productivity and system improvements, with many state wool boards lacking functionality and basic infrastructure.

(ii) Strategies and actions

Considering current climate scenario which has become hotter and warmer every passing year and the adaptation and mitigation measures being under way, two scenarios with respect to wool production by 2047 could be envisaged. Under scenario 1 (continued climate change), current level of wool production in the country shall suffice and even be reduced. In scenario 2 (climate change addressed), the 25 percent decline in wool production from 47.5 million kg in 2012 to just 33.6 million kg in 2022 will have to be reversed through appropriate technology integration and use.

Options like re-establishing the number of rams and wethers shorn to at least the 2016 level numbers of around 48-50 million will have to be explored, if necessary, by suitable directives so as to maintain a minimum of 6 percent growth in ethical and traditional woolen products like kullu shawls, Kashmiri scarfs etc. Since woolen carpets have a maximum share of 80 percent of total woolen products exported from India, it needs to be supported and sustained by revamping the sheep and wool boards in different states with adequate support base, creating sustainable grazing and pasture management systems, and facilitating Responsible Wool Standard (RWS) certification to maximize the economic benefits from wool.

As per the estimates, sheep population is expected to grow to 122 million by 2047 though majority will be mutton-producing sheep breeds that yield coarse wool. Therefore, the estimated production of coarse wool will be 30 million kg, medium wool 20 million kg and fine wool 5 million kg and a total expected wool production of 55 million kg by 2047. Accordingly, the health and efficiency of existing wool handling and processing infrastructure will have to be assessed and tuned to the requirement of 2047 technology platform.

High-value fiber production need a focus with promoting rearing of changthangi & gaddi goats and gaddi sheep in the hilly areas of Himalayas with comparable climate conditions.

The systematic and comprehensive plans for cross breeding projects with Merino especially in high altitude areas can also help in the higher production and productivity of quality fiber.

The breeding strategies will have to be directed towards increasing the fecundity of the sheep so as to obtain higher number of kids and higher production of wool with lower number of dams. For this, breed like ICAR-CSWRI- Avishan should be popularized and propagated.

Research organizations have developed value-added products from coarse wool, but their commercial adoption remained low. This is largely due to limited awareness and a lack of entrepreneurial involvement in the sector. To enhance the economic utilization of coarse wool, it is crucial to increase awareness about these products and provide government support to both the products and the entrepreneurs.

There is need to develop a cluster based wool processing centers with complete facilities of effluent treatment plant.

To boost the export market, it is essential to popularize branding through enhanced traceability using Blockchain technology that highlights the origin, quality, and sustainability of the products. Implementing Geographical Indication (GI) tags for specific types of wool, such as pashmina, can further enhance market appeal and credibility.

Precision farming technology use in sheep and goats for wool and fiber production, drone/ satellite mapping of migratory routes, providing incentives to eco-system service providers along such routes and creation of bare minimum shelter and health facilities to both pastoralists and the animals are envisioned.

Promotion and certification of organic wool production is foreseen in foreseeable future.

Attracting the youth to this sector of economy equipped with latest technology knowhow is an area to be explored.

6.4. Animal by-product sector

Efficient utilization of animal by-products/ wastes for economy-of-scale (Circular Economy) and environmental concerns is an important upcoming area.

- Total energy production by 2047 is expected to be 27600 GWH and 82.8 MT dry slurry at Rs. 17360 crores (present rate of energy is Rs 6.29/KWH) + 820 crores for dry manure.
- India is producing 220 million hides and skins and tanning them into 3.42 billion sqft of leather annually through 2200 registered tanneries. India is the 4th largest exporter of footwear, leather and leather products with a value of US$ $ 3.68 billion (2020-21). This contribution has to be taken to near doubling.
- Though India has the largest livestock population and approximately eight million tons of animal biomass is available, even then, the animal

by-product processing industry is neither developed nor properly organized, which is why the country has to import various processed animal by-products net, approximately 80281 tons, accounting for more than Rs 2000 crores on foreign exchequer. This has to be reversed.

- There are only six major gelatin production units in India. The Indian gelatine market's value is USD 111.8 million this year. With an appropriate strategy and policy, it is projected to register a CAGR of 5.34% over the next five years.
- In 2017, India produced only 14 MW of Biogas energy from 5 million Biogas Plants. This needs to be scaled up manyfold.

6.4.1. Strategy and action plan

- **Strengthening of infrastructure and facilities**: Presently, there are about 4000 registered public slaughterhouses, and only 150 modern units are engaged in by-product utilization and processing of meat-cum-bone meal, bone ash, tallow, lard, etc. This number should be increased commensurate with the projected quantity of resources (as indicated above) available for processing.
- **Collection of by-products**: As clandestine slaughtering and selling of hot meat are common, and the processing of meat is limited to only 3-4%, the collection of by-products from registered and unregistered slaughter houses and their transportation to rendering/by-product processing centers is an important impediment. The collection of waste needs to be interwoven with a smart city/ municipality waste collection program, and arrangements made for their processing within the district by establishing by-product processing centers of varying capacities, depending on the quantum of collection.
- **Research & development**: R&D efforts on processing by-products into *"High-Value, Low-Volume"* ones (viz., bone morphogenic proteins, pharma or food gelatin, neat's foot oil, collagen strips, etc.) are very limited. The technologies developed in some Indian laboratories have not been translated into industrial applications. A major R&D program in this highly paying area is needed. Such programs may also include by-product processing-related environmental concerns with an eye on a pollution-free industrial set-up.
- **Trained human resource**: Very few institutes (CLRI, NRC-Meat, etc.) in India provide training or extend vocational courses on some aspects of by-product processing. More such institutions will be needed to support the sector with trained manpower.

- **Socio-ethical issues**: NABARD and the Department of Animal Husbandry, GoI introduced various schemes related to carcass utilization. The scheme for the establishment of solid waste & carcass utilization plants was also introduced under 100 smart city projects, but still very few units are functional, presumably due to public outcry/ sentiments against the establishment of such units. Such problems should be mutually addressed with civil society organizations and other stakeholders.

  Small ruminant skin and hides require special attention because they form almost 90 percent of the total volume of the leather industry. The market price of small ruminant skin is as low as Rs 10-15/piece; therefore, additional research is necessary to utilize skin in collagen or gelatin production to increase its demand. Similarly, poultry feathers, etc., processing.

- **Broadening of support base**: Based on the Department of Animal Husbandry, Dairying and Fisheries (DAHDF) Annual Report 2023, the by-product industry contributed approximately Rs 28,000 crores, accounting for 7.8% of the total meat group worth Rs 3,80,755 crores at current prices in 2020-21. However, their economic potential remains untapped mainly compared to developed nations (including China), where they contribute 25-30% of the total meat value. Therefore, a specially designated scheme should be launched to leverage this sector's benefits.

7. Livestock Extension

By the year 2047, India will be at the forefront of global agricultural innovation and socio-economic development, driven by a robust, science-led production system. All stakeholders engaged in livestock and poultry production should be tuned to become technology user-friendly through an empowered extension service. For this, the extension system will have to be oriented towards (i) reskilling & upskilling the skilled, (ii) skilling the semi-skilled, and (iii) skilling the unskilled with different information and technology dissemination canvases.

8. Explore Newer Livestock Centric Science and Economic Opportunities

- Animals as bioreactors/pharmaco-farming for the production of therapeutic proteins for humans.

- Animals for xenotransplantation – organ donors for humans.
- Animals as a walking factory for food and nutrition.
- Animals as a biofertilizer and pesticide factory for natural/ organic farming.
- Animals as a power-generating unit- biogas.
- Animal farms are used as fodder trees/agroforestry units, with the provision of capturing and cultivating solar power (Vetyvoltaic) as the third crop for internal use and sale to power grids.

9. Epilogue

The livestock and poultry sector Vision, Mission, Goals and strategic approach envisioned for Animal Food Source sufficiency and surplus by 2047 has been articulated separately for Dairy, Poultry, Meat, Fibre/ Wool sub-sector, Animal by-product power both for naturo-organic agriculture and fossil fuel free energy generation, tapping of gelatin market through Start Up etc ventures together with generation and use of frontier and time matching technologies like pharmaco-farming (animals as bioreactor factory, organ donor option) and capturing of solar power using technology like Vety-Voltaic etc. As the sector, together with others, enter into further challenges, the requirement of skilled human resource on continued basis has also been indicated besides penning down the likely requirement of animal source food and the means to achieve that. In order to operationalise the vision, it is proposed to constitute Sector-specific Task Forces to develop detailed programs with anticipated budgets, identifying leading institutions and partner organizations for each touch point starting from production-processing-packaging-branding and consumption value chain.

10. References

APEDA. (2024). Agricultural and Processed Food Products Export Development Authority. https://apeda.gov.in/apedawebsite/SubHead_Products/Buffalo_Meat.htm

Chand, R., & Singh, J. (2023). From Green Revolution to Amrit Kaal: Lessons and way forward for Indian agriculture (NITI Working Paper 02/2023). NITI Aayog.

Confederation of Indian Industry. (2022). Food processing vision 2047. New Delhi. https://apeda.gov.in/apedawebsite/Announcements/List_of_Abattoirs_meat.htm

Department of Animal Husbandry and Dairying. (2023). Annual report 2022–23. Government of India.

Department of Animal Husbandry and Dairying. (2023). Basic animal husbandry statistics (BAHS)–2023. Government of India.

DGCIS. (2024). Annual statistics 2023–24. Directorate General of Commercial Intelligence and Statistics, Ministry of Commerce, Government of India.

Government of India. (2024). Union budget 2023–24. National Portal of India. https://www.india.gov.in/spotlight/union-budget-2023-2024#:~:text=The%20Vision%20for%20'Amrit%20Kaal,Growth%20%26%20Job%20creation

Kandpal, A., Birthal, P. S., & Mishra, S. (2024). From research to impact: Payoffs to investment in agricultural research and extension in India (Policy Paper 44, pp. 64). ICAR–National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi.

National Dairy Development Board. (2018). Annual report 2017–18. https://www.nddb.coop/sites/default/files/NDDB_AR_2017-18_%28Eng%29.pdf

National Dairy Development Board. (2023). National workshop on water management in dairy industry (2023). Anand.

NITI Aayog. (2018). Demand and supply projections towards 2033: The working group report–2018: Crops, livestock, fisheries and agricultural inputs. New Delhi.

NITI Aayog. (2024). Working group report on demand and supply of crops and livestock products and agriculture inputs. New Delhi.

5 Fisheries Sector

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1. Context

India's fisheries sector has exhibited remarkable growth and resilience over the years, evolving into a pivotal component of the country's agriculture and food industry. From a modest production of 24.42 lakh tons in 1980, the sector has experienced a rapid rise, reaching an astounding 162.48 lakh tons by 2022-23. This remarkable expansion is characterized by a significant shift towards inland and coastal production, which now stands at 121.21 lakh tons and exceeds marine production at 41.27 lakh tons (FAO, 2024a). The sector has maintained a robust average annual growth rate of 10.34%, reflecting its dynamic adaptation to changing environments and market demands. This surge in production has had a considerable impact on the country's economy, contributing 6.44% to the Gross Value Added (GVA) in the agriculture sector (GoI, 2020a). Additionally, the fisheries sector has marked its prominence in the global market, with the export of 13 lakh tons of fish and fishery products generating revenue of over Rs. 60,000 crore and witnessing an annual growth rate of 31.71%. Beyond its economic contributions, the fisheries sector is a vital source of employment, providing livelihood opportunities to approximately 28 million people nationwide (DoF, 2020). This includes many jobs spanning from fishing, processing, and marketing, highlighting the sector's pivotal role in socio-economic development and community welfare.

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India's fisheries sector provides enormous potential in extending its reach to hitherto underexploited resources in both marine and inland waters; sizeable hikes in production and productivity from aquaculture; productive integration with other farming sectors such as agriculture, horticulture, poultry, and livestock; expansion of non-food fisheries such as ornamental; and in enhancing the availability of nutritious fish protein rich in omega-3 fatty acids to the nation's growing population. On the environmental front, ponds, tanks and floodplains can play a very important role in harvesting and holding rainwater and serving as a valuable ameliorative agent for recharging groundwater.

Despite the progress, India still lags behind in per capita fish consumption (7.89 kg/year) compared to the global average (20.25 kg/year) (FAO, 2024a, NAAS, 2024a). With the growing population of the country and the increasing requirements for fish protein, the need to produce an adequate quantity of fish at a reasonable price is more compelling than ever before. To match such demands and ensure a growth trajectory that fulfils the requirements of today and leaves an equally better fishery for tomorrow, it is necessary for the country to develop a sound National Fisheries Policy framework. The Policy will provide the blueprint to optimally harness the capture and culture of fishery resources that would help sustain the desired production and productivity levels. This policy framework is also expected to guide similar initiatives at the State and Union Territory levels in the coming period.

1.1. Marine fisheries

The potential of the fisheries sector in general and the marine fisheries sub-sector in particular was recognised quite early in India's development planning. Marine fisheries play an important role in trade and commerce and promote employment and livelihoods of coastal communities. After the declaration of the EEZ in 1976, the sea area available to India is estimated at 2.02 million km^2, a shelf area of 0.372 million km^2, and a coastline of 8118 km (ICAR, 2015b). With sovereign rights on the EEZ, India has also acquired the responsibility to conserve, develop and optimally harness the marine living resources within this area. The marine fisher population in India is estimated at 3.77 million, of which 0.93 million are active fishers (ICAR, 2018). About 0.52 million people are engaged in fishing and allied activities, of which 69% are women (ICAR, 2018). Women are especially active in fish marketing, constituting about 86% of the participants. About 14,000 women are also engaged in fish seed collection, and an equal number in the shell collection activities

(ICAR, 2018). The predominance of small-scale fisheries characterises the marine fisheries sector as a whole.

1.2. Inland fisheries

The inland capture fisheries resources are as vast and varied as the marine fisheries resources, and their importance as a source of livelihoods, food, and nutrition for the population has been no less than their marine counterpart. The riparian communities along the major river systems of India have been as old and traditional as the marine fishers. However, with the changing scenario in the inland sector, their migration to other sources of livelihoods is more prominent than any other food production sector.

The inland capture fisheries resources include a riverine length of 2,01,496 km (including the tributaries and irrigational canals), 3.52 million ha of small and large reservoirs, 1.2 million ha of floodplains, etc (NAAS, 2016). The total area available for the inland fishery is estimated at 8.24 million ha, excluding rivers and canals (NAAS, 2016). The total inland fisher population is approximately 24.29 million (DoF, 2020).

2. Challenges and Opportunities

2.1. Global challenges and opportunities

According to the recent FAO's Global State of Fisheries and Aquaculture (SOFIA, 2022) report, aquatic food production is forecast to increase by a further 15% by 2030, mainly by intensifying and expanding sustainable aquaculture production. Such growth should preserve aquatic ecosystem health, prevent pollution, and protect biodiversity and social equality. However, it also predicts that aquaculture production's average annual growth rate will slow over the next decade to less than half the rate observed in the previous decade, dropping from 4.2% (2010-2020) to 2% (2020-2030) (FAO, 2024a). Several factors are expected to contribute to this slowdown. These are broader adoption and enforcement of environmental regulations; reduced water availability and suitable production locations; increasing outbreaks of aquatic animal diseases related to intensive production practices; and decreasing aquaculture productivity gains.

The opportunity would still lie with the Asian countries, including India, as they are expected to continue to dominate the aquaculture sector, maintaining their share of 88% of 2030 global aquaculture production, and be responsible for more than 88% of the increase in production by 2030. The report further predicts that all farmed groups of species will continue to increase. Still, rates of growth will be uneven across groups, and the quantitative importance of different species will change as a consequence. In general, species that require larger proportions of fishmeal and fish oil in their diets are expected to grow more slowly owing to higher prices and reduced availability of fishmeal.

FAO envisages a “Blue Transformation” strategy to steer the sector during the next decade with four specific goals: (i) increase the development and adoption of sustainable aquaculture practices; (ii) integrate aquaculture into national, regional and global development strategies and food policies; (iii) expand and intensify aquaculture production to meet the growing demand for aquatic food and enhance inclusive livelihoods; and (iv) improve capacities at all levels to adopt innovative technology and management practices for a more efficient and resilient aquaculture industry.

The burden on the aquatic environment is increasing due to continued urbanization, industrialisation, and climate change (FAO, 2020, World Bank, 2013). Coastal areas face pressures from development activities, while urban and industrial effluents impact inland water bodies. Climate change is causing warming temperatures, sea level rise, ocean acidification, and changes in precipitation patterns, which can have severe consequences for aquatic ecosystems and the fisheries they support (FAO, 2020).

Many of the world’s fish stocks are over-exploited, with fish stocks declining at unsustainable rates due to excessive fishing pressure. Restoring and maintaining healthy fish populations is crucial. Activities such as coastal development, pollution, and destructive fishing practices are degrading critical habitats like coral reefs, mangroves, and estuaries that serve as nurseries for many fish species. With growing populations and increasing demand for seafood as a vital source of protein and nutrients, sustainable fisheries management is essential to ensure food security and nutrition, especially in developing coastal communities.

Illegal, Unreported, and Unregulated (IUU) fishing undermines conservation efforts, distorts market competition, and threatens the livelihoods of legitimate fishers. Combatting this illicit activity is a global priority. The unintended catch of non-target species, including marine mammals, turtles, and seabirds, is a significant conservation concern, as is the wasteful practice of discarding edible fish at sea.

Climate change-related risks pose one of the major challenges for the fisheries sector globally. IPCC’s recent sixth assessment report reiterated the acceleration of global warming and placed unprecedented emphasis on adaptation, highlighting the urgency of scaling up adaptation actions. Fisheries and aquaculture make a minor contribution to global carbon emissions. But there are opportunities for decarbonisation along the fisheries and aquaculture value chain, increasing its efficiency by reducing fish waste and losses, including for small-scale fishers and fish farmers. Decarbonisation technologies already exist; however, access and upscaling remain challenging due to the high costs.

Emerging and frontier technologies like artificial intelligence (AI), internet of things (IoT), blockchain, and nanotechnology provide opportunities to develop high-tech aquaculture systems (UNDP, 2025). These advanced technologies can enable precision farming, automation, real-time monitoring, and optimization of production processes, leading to improved efficiency, sustainability, and profitability in aquaculture operations worldwide. However, the concerns raised about these emerging technologies, such as displacement of labor and growing unemployment, digital divide and inequity between small-scale and large-scale operators, etc., need to be taken into account. Leveraging precision fishing technology can help reduce fishing operations' carbon footprint and promote sustainable resource utilization. Advancements in areas such as fuel-efficient vessels, selective fishing gear, real-time catch monitoring, and electronic monitoring can contribute to developing a green and responsible fishing industry.

There is a growing demand for the development of antibiotic-free fish production systems, driven by concerns over antimicrobial resistance and consumer preferences for safer, more sustainable food products. This requires innovations in disease prevention, alternative treatments, and improved biosecurity measures in aquaculture facilities. Consumers, particularly in developed nations, are becoming increasingly aware of the need for safe, nutritious, and fortified fish products produced through eco-friendly and sustainable practices. This presents an opportunity for aquaculture and fisheries businesses to differentiate their products and capture premium market segments by adopting responsible and traceable production methods.

2.2. National challenges and opportunities

The fisheries sector in India faces several challenges, including minimal technology application and productivity levels that are less than optimal compared to Southeast Asian countries. Genetic selection has been limited to 1-2 traits in carps, while countries like Europe and East Asia have advanced to selecting for 5-6 traits in species like salmonids and tilapia. There is limited access to and exchange of globally available technologies for open water and precision aquaculture and inadequate knowledge of genomic diversity. The lack of vaccines, therapeutics, on-farm diagnostics, and efficient delivery systems poses a significant hurdle. Moreover, there is an absence of long-term aquatic ecosystem change studies and understanding of human-ecosystem interactions, compounded by inadequate R&D infrastructure for high-throughput genome analysis and mining given India's rich aquatic species diversity.

Non-transparent, data-deficient fisheries, characterized by poor monitoring, control, and surveillance, as well as inadequate knowledge of stock identities and fishing grounds, impede effective management. The excessive use of fossil fuels leads to an increased carbon footprint and reduced productivity, while the dependence on conventional fishing systems persists due to the non-adoption of available technologies. In the post-harvest sector, there is a low integration of frontier technologies, high dependence on capital-intensive imported machinery, low adoption of farm-to-fork traceability technologies, and poor integration among supply chain nodes. Inadequate post-harvest fish handling and cold chain management further exacerbate the challenges.

A significant issue is the unrecognised contribution of small-scale fishers, women, and fish workers due to the non-availability of sex-disaggregated data. The predominance of traditional, input and energy-intensive technologies with high environmental footprints and low adoption rates, such as the lack of miniaturisation of analytical/processing equipment and bio-refinery, poses a challenge. Limited availability of indigenous processing machinery and inadequate implementation of food safety and traceability measures across the value chain further hamper progress.

A significant limitation is the lack of synergies in terms of interdisciplinary and multispecialty human capital and R&D teams. Additionally, there is a substantial gap between the demand and supply of professional (4500 vs. 1500) and paraprofessional (28000 vs. 3500) human resources in fisheries and aquaculture. Limited mobility and exchange of human resources and partnerships within Asia, as well as an incoherent science (R&D)-policy interface in informing fisheries management, further impede progress in the sector.

The supply chain is the weakest link in the entire series of operations in the fisheries sector in India. It results in considerable losses to the operators and the national economy. Improving the supply chain from 'boat to plate' and 'farm to fork' can benefit fish harvesters, farmers, processors, and consumers. This one area has remained grossly neglected and needs to be improved significantly to reduce post-harvest losses, provide safe food to people, and improve the economy of the participants in the chain. Improvements in the supply chain would necessitate the following major policy initiatives.

While the country has modern processing infrastructure catering to the export market, the same is true for domestic marketing. Fish is sold most unhygienically at the landing sites and/or wholesale/retail markets. Despite substantial assistance being made available by the Government for setting up/improving fish handling centers (FHCs) and fish landing centers FLCs and fish markets, the situation has not improved. This is one of the reasons why India has been witnessing a slower growth rate in fish consumption over the years compared to many Asian countries such as Thailand, Vietnam, Malaysia and even Sri Lanka. Unfortunately, there has also been little consumer resistance to purchasing fish handled in the most unhygienic manner.

The environment in both marine and inland waters in India is under stress due to pollution and is probably one of the reasons for the decline in fish stocks. With the increasing anthropogenic activities on land and inadequate mechanisms for effluent treatment, the abundance of solid waste and in particular plastics (especially micro-plastics) has increased manifold in the sea as well as in the inland waters, resulting in negative impacts on the fauna and flora. There are also several alarming reports that indicate the movement of microplastics back to human beings through the fish food cycle.

Wanton and un-wanton dumping of fishing nets in the oceans also contributes to micro-particles, besides the nets engaging in ghost fishing, which affects fish stocks. The policy directives will strengthen regulatory mechanisms to control pollutants to ensure that land and sea-based pollution is effectively controlled and the ecosystems are monitored. Fishers will make all-out efforts to ensure that fishing vessels do not contribute to marine pollution by considering the required measures, in the design and construction of fishing vessels and subsequently in the use of gear.

3. Vision and Mission

3.1. Vision

By 2047, India will emerge as a global leader in sustainable, climate-resilient, technologically advanced fisheries and aquaculture. The sector will be transformed into a state-of-the-art, green, resource-sensitive, equitable, and competitive industry, underpinned by scientifically managed and well-sustained aquatic ecosystems and biodiversity.

3.2. Mission

Aquaculture will achieve technological self-reliance and global eminence, driven by cutting-edge genetics, biotechnology, precision farming, and renewable energy integration innovations. Genetically improved and technology-augmented aquaculture systems will optimize productivity, quality, and resilience, ensuring all food, nutrition, and livelihood security.

Capture fisheries will be sustainable, monitored, assessed, regulated, and traceable, safeguarding marine, coastal, and inland ecosystems. Advanced stock assessment, monitoring, control, and surveillance systems will promote transparency and traceability, enabling informed management decisions and ecosystem conservation.

Indigenous technologies and machines with low environmental footprints will facilitate the zero-waste utilization of aquatic resources, yielding safe, nutritious, and consumer-friendly products. Blockchain-enabled traceability, intelligent fish handling, and modern retail chains will ensure food safety, quality assurance, and fair value realisation for all stakeholders.

Interdisciplinary research and development will drive innovation, harnessing advances in genomics, biotechnology, artificial intelligence, nanotechnology, and renewable energy. A robust ecosystem of incubation centers, skill development programs, and policy research will nurture a globally competitive workforce, positioning India as a thought leader in sustainable fisheries and aquaculture development.

Through international cooperation, inclusive stakeholder engagement, and evidence-based policymaking, India will champion the sustainable management of shared resources, ecosystem restoration, and climate change adaptation and mitigation strategies, fostering resilient aquatic ecosystems and conserving biodiversity for future generations.

4. Priority Areas

4.1. Genetically improved, technology augmented, resilient & responsible aquaculture systems (GITA-RAS)

The GITA-RAS program aims to utilize genetic and genomic diversity for a 20% increase in productivity and quality enhancement in aquaculture systems. It involves upscaling ready-to-adopt technology packages for seed, feed, health, and grow-out of freshwater, marine, ornamental, seaweed, and aquaculture in open water and degraded land areas. The program focuses on developing hi-tech aquaculture systems (utilizing advances in AI, ICT, space technology, nanotechnology, etc.) for four high-value species in open sea/reservoir automated cages, biofloc, and recirculating aquaculture systems (RAS). It also explores viable technologies for *in-vitro* fish meat production and marine microalgae culture. Additionally, the program aims to use renewable energy (up to 30- 40%) in hi-tech culture systems and establish cellular fish culture and marine microalgae parks in suitable marine hubs (ICAR, 2015a).

4.1.1. Mariculture

The Government of India, recognizing that the demand for seafood will be increasing year after year and also realizing that marine capture fisheries alone might not be able to meet the additional seafood demands, has initiated the development of mariculture in the country's coastal areas. Based on the potential areas available for mariculture development in the country, the annual production of 4-8 Mt has been projected.

As mariculture development in the country is in nascent stage, the policy initiatives would be manifold, starting with developing a blueprint of suitable sites/areas along the Indian coastline with a leasing policy following a Marine Spatial Planning (MSP) approach. This would allow the selection process of identifying suitable species for farming in a particular area and allocation of space on a priority basis to small and traditional fishers for open sea cage farming. Commercial-scale production of seed of potential species and their cage farming may be promoted in specifically identified ocean spaces, in particular in waters beyond 12 nautical miles, but with adequate safeguards and without affecting regular fishing, shipping and other maritime activities.

On the Indian coastline, which is almost straight with large areas exposed to surf and tidal influence, cages have to be set up in open waters, exposing them to the elements of nature, as well as in sites located in bays, coves, and sheltered areas and are less vulnerable to high winds and currents. Therefore, one of the key requirements to popularize mariculture would be the availability of sturdy cages and moorings that can withstand the harsh marine environment.

While sufficient progress has been made in the development of technologies for breeding and larval rearing of a number of candidate species (*e.g.*

cobia, silver pompano, Indian pompano, orange-spotted grouper, emperor sea-bream, John's snapper and vermiculated spinefoot, green and brown mussels and edible oyster), the availability of quality seed in sufficient quantities would kick-start the activities on a larger-scale and also make farming cost-effective. The role of R&D and industry is prime in this regard to cater to the needs of the mariculture farmers and entrepreneurs. Policy initiatives will provide the required support for promoting commercially viable seed production technologies and developing brood banks for candidate species and hatcheries to scale up seed production and availability to meet the requirements of farmers. The PPP will also be important in the entire mariculture developmental process (ICAR, 2015b).

4.1.2. Seaweed farming

Like aquaculture and mariculture, urban farming in the country is also untapped, and demand for seaweed is increasing for hydrocolloids, cosmetics, supplements, and as a potential biofuel source. This sub-sector offers immense scope for value creation along the value chain and can contribute significantly to the economy in the coastal country. There are about 844 seaweed species in India with a standing stock of about 58,715 tons (NAAS, 2024b). Seaweeds are abundant along the Tamil Nadu, Gujarat and Diu coasts and around the Lakshadweep and Andaman & Nicobar Islands. Rich seaweed beds occur around Mumbai, Ratnagiri (Maharashtra), Goa, Karwar (Karnataka), Varkala, Vizhinjam (Kerala) and Pulicat (Tamil Nadu), East Godavari to Srikakulam coast (Andhra Pradesh) and Chilka (Odisha). However, indiscriminate and unorganized harvesting has resulted in the depletion of natural resources.

While the initial trial of seaweed farming was carried out during the early and mid-1980s, the activity has yet to popularize. Unlike other fisheries activities, local demand for seaweed for food purposes is minimal. Nearly all domestic seaweed production is used in the industrial sector, and, therefore, the production would necessitate strong backward and forward linkages. The policy would ensure that such linkages are developed while ready-to-use technologies and other inputs are made available.

Suitable areas for seaweed farming have been identified along the coastline of Gujarat, Diu, Lakshadweep, Tamil Nadu, and Andhra Pradesh by the research institutions in the country. To promote seaweed farming and attract the fishers, initially, seaweed seedbanks using sexual reproduction methods, complementing the presently adopted widely popular vegetative/asexual propagation methods, can be set up on the Tamil Nadu coast, where maximum seaweed farming is currently being carried out. Later, it can be extended to the coasts of Gujarat and other places along the coastline. The species that can be promoted on a larger scale is *Kappaphycus alvarezii* and potential varieties of indigenous seaweeds (agarophytes and alginophytes).

Offshore waters also offer opportunities for raising seaweeds, especially through Integrated Multi-Trophic Aquaculture Systems (IMTA), where finfish species such as cobia can be raised along with seaweeds. While moving towards large-scale seaweed farming, the harvesting of seaweed from the wild would be discouraged unless sustainable management plans are in place.

Seaweed farming would be instrumental in creating livelihoods for fishers and rural women. Women would be encouraged to form self-help groups/cooperatives/producers' associations to undertake seaweed production and processing through training, access to public finance, and marketing support.

4.1.3. Ornamental fish farming

Ornamental fish are a relatively small but active component of the international fish trade. Maintaining an aquarium is a popular hobby, and the global trade of ornamental fish is estimated at US$ 18-20 billion annually. Due to its diverse biological resources, India has many commercial and potent ornamental fish resources. About 374 freshwater species and over 300 marine species are suitable for the ornamental fishery.

While the value of the domestic market for the ornamental fishery is estimated at about Rs. 500 crores, the activity is limited to some specific areas in West Bengal, Tamil Nadu, Maharashtra, North-eastern States and the Islands. The policy would encourage setting up domestic units to enhance ornamental fish production, develop an end-to-end supply chain, and maintain habitats to boost rural livelihoods. The policy would also encourage consumer education, the benefits of maintaining an aquarium, and promote the installation of aquaria in public institutions. Women and youth will receive focus through appropriate interventions.

It is estimated that about 85% of ornamental species are harvested from the wild, chiefly from the hill streams of the Northeastern States or the prime coral habitats located along specific stretches of the coastline and the two Island Territories. As these wild-sourced species command higher prices, the pressure on their harvesting is substantial and increasing. Policy interventions will ensure that such resources are optimally harvested, and necessary controls will be implemented to ensure the sustainable use of the wild ornamental germplasm.

4.1.4. Productive and sustainable utilization of inland saline soils

The area under salt-affected soils in the country is estimated to be about 6.73 million ha (Mha) with the States of Gujarat (2.23 Mha), Uttar Pradesh (1.37 Mha), Maharashtra (0.61 Mha), West Bengal (0.44 Mha) and Rajasthan (0.38 Mha) together accounting for almost 75% of the saline and sodic soils in the country (ICAR, 2015a). The other States where such resources exist include Punjab and Haryana. Irrational use of canal water is a major cause of soil salinisation. Saline soils bring down productivity and render the soil unsuitable for agriculture and other purposes such as construction. However, field-tested technologies are available for utilizing such lands through farming finfish and shellfish. Such technologies have already shown potential in saline areas of Haryana, Punjab, Rajasthan and UP, where farmers have successfully raised black tiger shrimp (*Penaeus monodon*) and Pacific whiteleg shrimp *Litopenaeus vannamei*. Unlike coastal saline areas, there is also a negligible environmental impact as the inland saline areas have few alternate uses. However, wastewater disposal from aquaculture needs due consideration to prevent any long-term consequences.

The key policy initiative would entail the identification of potential areas and their allocation for aquaculture; imparting best technologies to the farmers, including the sustainable use of groundwater wherever required; extension support and hand-holding; introduction of potential finfish species such as sea bass and mullets for risk reduction; sound mechanisms for treatment and disposal of wastewater from aquaculture; and establishing forward and backward linkages for the supply of seed and feed of species such as Pacific white leg shrimp, mullets and sea bass and subsequent assistance in the marketing of the produce. Where larger areas suitable for farming in saline soils are available, the development of Special Aquaculture Zones through PPP arrangements would also be considered (DoF, 2020).

4.2. Fisheries for blue economy: sustainable, monitored, assessed, regulated & traceable fisheries (S.M.A.R.T.)

The S.M.A.R.T. Fisheries for Blue Economy program involves remote sensing and GIS-based assessment of all major aquatic ecosystems and valuation of ecosystem services consisting of marine, coastal and inland resources. It aims to develop predictive tools to project and identify expected tipping points of the ecosystems and prospect climate-resilient aquatic germplasm and allele mining for abiotic stress management. The program focuses on transparent and traceable marine fisheries through advanced stock assessment and effective monitoring, control, and surveillance (MCS) systems, such as smart tokens, digital trip sheets, real-time catch data logs, and deep learning-based species detection to exclude non-target fish. It promotes energy-efficient fishing vessels using hybrid energy and partially replacing fossil fuels (ICAR, 2015b).

The program also involves developing a national blueprint for an inclusive spatio-temporal plan for marine conservation and management, complete genome sequencing of 500 species, and IoT and AI-based automated catch monitoring and genetic stock assessment methods using a structured ecosystem approach to fisheries management (EAFM). It aims to develop energy-smart industrial fishing fleets driven by renewable energy sources, AI-embedded selective gear systems, innovative ecosystem restoration programs using improved artificial propagation (including seed ranching), artificial fish habitats, and drone-based seed disseminations. The program also accelerates coral reef resilience through heat-evolved symbionts and cell line-based propagation, promoting healthy and climate-resilient freshwater and marine ecosystems, sustaining fish species diversity and ecosystem services. It involves live mapping of ecosystem changes in marine/freshwater hotspots for preparedness, mitigation, and adaptation to extreme event impacts. The program aims to establish a global repository of aquatic germplasm and genomic data, including genetically engineered stress-tolerant strains, and achieve real-time knowledge of the fishery footprint in the Indian Exclusive Economic Zone (EEZ), aiding safe, efficient, and sustainable catch of 5 Mt per year, as well as precision AI-enabled green fishing with total replacement of fossil fuels for fishing operations.

4.2.1. Marine spatial planning

India's coastal and marine environment is one of the world's richest ecosystems with high productivity. The Blue Economy provides an excellent opportunity to access these natural resources and ensure food security and gainful employment, but only if the resources are sustainably harvested and well-managed. India has developed a working definition of Blue Economy: "it refers to exploring and optimizing the potential of the oceans and seas, which are under India's legal jurisdiction for socio-economic development, while preserving the health of the oceans. The Blue Economy links production and consumption to capacity and envisages an integrated approach to economic development and environmental sustainability. It covers both the marine, that is offshore resources, as well as the coastal, that is onshore resources".

The fisheries and aquaculture sector are emerging as a dynamic segment of the Indian economy and is positioned towards a significant growth trajectory in the coming period. Fisheries and aquaculture are also important constituents of Blue Economy initiatives. These initiative aims to promote investment and innovation in support of food security, poverty reduction, and the sustainable management of aquatic resources. The initiative takes an overall approach towards improving sustainable growth and management of aquatic resources, with special attention provided to the seafood value chain.

However, considering the competing demands for ocean space, the need for Marine Spatial Planning (MSP), which is an essential tool for implementing the Blue Economy, assumes significance. With the growing demand for mineral and oil exploration/extraction from the seas, the increasing volumes of maritime commercial traffic and the reservation of spaces for strategic defence purposes, the available space for fisheries is diminishing. Keeping these contemporary developments in view, the policy will emphasize the need for sound MSP to ensure that all economic activities get their due space and, in the process, reduce conflicts. Where required, necessary research support would also be solicited from the Research Institutions.

4.2.2. Regulating the sustainable and wise use of inland and marine resources

Considering the developments in exploiting the resources in waters beyond 12 nm, there is an urgent need to enact comprehensive legislation for fishing regulation by the national fleet in the EEZ and the ABNJ. Comprehensive legislation is also required because it would clearly set the agenda for the nodal agency responsible for the management of EEZ, and it would be easier for the fishers to follow a set of clear regulations and for the MCS agencies to implement them.

Similarly, a Model Bill for Inland Fisheries and Aquaculture is needed, which the States/UTs can use to repeal their existing Acts or amend them to make them contemporary and comply with the topical requirements.

4.2.3. Regulating fish meal production and wild collection of juveniles

India is a new entrant in fishmeal production. All these years, fish meals have been imported, but now, after meeting the domestic requirements, India is a net exporter of fish meals. A policy direction on fishmeal production and seed collection is also an urgent requirement for sustaining the sector. While usually concerned with aquaculture, fish meal and seed production happen at the crossroad of capture and culture fishery and can affect both. The seed collected from the wild for stocking in farm ponds or mariculture affects the population of many other discarded species while retaining the target species. Fish meal production units, while on one hand have helped in productive utilization of 'trash fish' but in the process of proliferation of such units, fishing vessels are now using destructive gear to ensure that large catches irrespective of size and conservation status are harvested to meet the increasing requirements of the fish meal plants. Large quantities of fish meal are produced using small-sized sardines, which has a negative impact on the sustainability of the sardine population. Policy initiatives will discourage the use of edible fish species for such conversion. Further, R&D on producing fish meal from alternative sources and sustainably harvested fisheries will be encouraged, and the total fish meal requirement for all sectors (poultry, aquaculture, etc.) will be estimated to ensure a steady supply of quality fish meal.

4.3. Technology-mediated value chain for safe and nutritious aquatic food/fish products (TVC-4-SNAP)

The TVC-4-SNAP program focuses on developing cost-effective and indigenous machineries with low environmental footprints for producing novel health foods, nutraceuticals, cosmeceuticals, and pharmaceutical products from aquatic resources. It involves establishing ICT-mediated fish market grids with blockchain-enabled traceability systems and cold chains for price integration and waste management. The program explores alternative strategies for producing antibiotic-free fish and develops expert systems for traceability, quality assurance, and safety. It aims to create a geo-coded and gendered occupational database of all actors across fish/aquatic product value chains and integrate circular economy principles in fish processing. The program promotes the establishment of intelligent fish landing centers and markets with stable price regimes, optimal market intermediation, and the production of fortified fish (2 species) and modern retail market chains with quality certification, niche labelling, and branding. It conducts market studies to widen the markets (export/domestic) and products, and provides R&D-based support systems for technology adoption, incubation centers, skill development, and regulatory frameworks. The program aims to develop indigenous technology-driven production of safe and high-value products from aquatic resources, ensuring better price/value realisation for fishers and their human development. It strives to double the domestic consumption of safe and fortified fish and triple the exports of high-value products targeted at specific market segments, with at least one-third being value-added products.

4.3.1. Improving the supply chain and value chain

Zero wastage: To reduce fish wastage in terms of physical and quality loss, policy initiatives will be directed towards improving the handling and storage of fish in the vessel. The deck is the first point of contact, and if the fish is handled and stored properly, the chances of contamination are minimized. The use of clean ice and/or provision of Refrigerated seawater/ slurry ice facilities is paramount, and it would be ensured that the fishing vessels are provisioned with clean ice and/or other such cooling facilities onboard.

Once the catch is landed, policy initiatives will aim at well-developed distribution channels and cold chain arrangements to move the harvest to the consumers in the shortest possible time. Reducing the number of nodal points in the supply chain and minimising the distribution channels is also important. Establishing a partnership of actors in the value chain is the key to realising the best product values. Appropriate revenue structures, which ensure adequate compensation to fishers and farmers and protect their livelihoods, are also necessary to ensure their participation in the value realisation.

With production from marine capture fisheries plateauing and wastage of fish across the supply chain not decreasing, there could be a scarcity of raw material for export in the coming years. Trade policies, including tariffs, also significantly shape fish production and international trade. The policy measures required for improving the value chain in the domestic market (as well as for exports) would include establishing a well-organized supply chain and making adequate facilities available at the landing sites, such as clean water, clean ice and proper storage. For implementing the Hazard Analysis Critical Control Point (HACCP) System based on the recognition that microbiological hazards exist at various points of the supply chain, policy measures will be implemented to control them.

Value-addition: Value-addition can start when the fish is out of water. Proper on-board handling, as mentioned earlier, can substantially reduce wastage and on-board gilling and gutting, and placing the fish in crates with adequate ice further enhances the value. On landing at the FH or the FLC, further value-addition can occur by dressing the fish, vacuum packing, etc. and then moving it to the retail markets. As we move up the value addition, values can be enhanced by adding specialized ingredients to increase nutritional value, increase shelf life, and realize the convenience of using fish products. There is also immense scope to develop non-food, pharmaceutical, and nutraceutical products.

Value-creation: Certification and labelling schemes and traceability for environmentally and socially responsible production will create new markets, and these products can be traded globally. These measures also focus on environmental concerns and strive to achieve sustainability in fisheries. Certification can also offer other benefits to producers in the form of improved market access and potential price improvements. Effective MCS and a 'blockchain' approach could boost transparency of the sector by providing means to trace and record the entire fish supply chain, and convince the public, industry and consumers about sustainability and food safety.

4.3.2. Developing domestic markets

Despite the immense health and nutrition benefits of fish, the slow pace of increase in fish consumption in the country has been raised occasionally, but the real pinch has been felt since the spread of the COVID-19 pandemic. With the closure of export markets, producers have felt the need to develop domestic markets to reduce dependence on exports. Fish may be included in the mid-day meal program to improve the nutritional requirements of school children.

The growth of online fish marketing has now created ample opportunities for the supply of processed fish to many consumers profitably. This shortening of the value chain will be remunerative for fishers as they will have an increasing share of the consumer's rupee. The processor can also ensure better value chain governance owing to the direct linkage with the fishers. Over time, if fishers can develop the required skills, they can establish captive value chains with end-to-end connectivity (DoF, 2020).

4.3.3. Promoting trade and food safety

India's fish trade remains heavily dependent on shrimps. It comprises about 40% of exports in quantity terms and 68% in value terms. In this scenario, the matter of concern is that during the last 24 years, while trade has increased by 13 times and quantity by 5 times, the nature of India's export basket remains the same. For long-term development, it is essential that India's export potential is diversified and the capture and culture fishery is fully realized. Further, it is also necessary for the Indian processing sector to move to higher-order value addition, considering key market requirements.

India has consolidated the US market but failed in the EU market. India has also successfully opened new markets in China, the Middle East, and Southeast Asia. A competitive and diversified offering will help India further consolidate its market position.

However, global trade is becoming increasingly subject to different barriers and filters. The high-value markets of the US, EU, and Japan are especially subject to increasing constraints, mainly on account of safety and hygiene and biodiversity conservation (*e.g., protection of* turtles and mammals). Therefore, focusing on quality control and maintaining traceability throughout the supply chain is necessary for ensuring competitiveness. It is important for India to be competitive through cost-effective technologies to capture new emerging markets.

4.4. Professional fisheries human resource for global knowledge leadership (HR-4-GloKeL)

The HR-4-GloKeL program aims to bridge the demand-supply gap in professional human resources by 50- 60% and partner with Agricultural Universities (AUS) to bridge the para-professional supply gap. It establishes a Center of Excellence (CoE) in Policy Research for data-driven decision-making. It aims to produce at least 10% of the global supply of smart and specialized fisheries professionals. The program strives to emerge as a leading think tank driving evidence-based policymaking and development interventions (ICAR, 2015a).

4.4.1. Data-base development

Sound data is a key prerequisite to sound policy formulation. With the fisheries sector growing manifold in the last four decades, mechanisms for data collection and their collation have lagged behind. While data on marine fish landings is collected regularly following internationally accepted methodologies and protocols, the same is not happening in other sectors. Except for the five-year census carried out for the marine fisheries sector, similar information is also unavailable for inland fisheries, including aquaculture. New tools related to Information Technology may be tapped to access, store and disseminate the data. Also, an integrated fisheries statistical system that covers all the states and UTs needs to be developed and hosted by the Department of Fisheries, Ministry of Fisheries, Animal Husbandry and Dairying, with a necessary support system for the states.

Building community institutions: A prerequisite for successful resource management is the appropriate specification of property rights, *i.e.* who owns the resource, who is responsible for conservation, who receives the gains from resource use, etc. In India, the issue of ownership is *de facto* ambiguous. While the Government, as a as a custodian of the people owns, owns the resource, the community also asserts its traditional right to ownership. One way to legitimise both positions is through co-management. The States of Kerala and Tamil Nadu and the UT of Puducherry have now set up co-management structures at different administrative tiers (village, district, state), including a charter of their rights, and duties and have also provided the legal/administrative support. Such models need to be upscaled to other inland and coastal States/UTs.

Developing a single-window system: A new department under the Ministry of Fisheries, Animal Husbandry & Dairying needs to be created as an umbrella agency focusing on governance, coordination and policy setting (in its area of Business) and harmonization amongst the States/UTS for effective fisheries governance. It will require establishing specialized agencies to carry out focused activities covering R&D, MCS, Trade, International relations, development, etc. The National Fisheries Development Board (NFDB) may give the mandate.

The fisheries sector deals with a range of institutions that fall within the purview of coastal State/UT Governments (DoF), Central Government (MFAH&D, MA&FW, MHAS, MCI, MEFCC, MWRRD&GR, MP, MD, MES, etc.) and scientific bodies. This pluralistic governance structure necessitates strong coordination between the MoFAH&D and the Coastal States/UTs on one hand, and different Ministries/Departments of the Union Government on the other. Further, similar cooperation between the States/UTs and within the State/UT will also be essential to ensure that fisheries and aquaculture are sustainably managed.

5. Roadmap during *Amrit Kaal*

5.1. Reforms in fisheries research

Research on sustainable fishing practices should be prioritized to prevent overexploitation and ensure long-term resource viability. Research efforts should also increase to develop efficient and environmentally friendly aquaculture techniques. This includes selective breeding programs for improved fish stock, disease-resistant varieties, and alternative feeds.

Allocate greater resources towards fisheries research to support infrastructure development, acquire advanced equipment, and attract skilled researchers. Modernize existing research facilities and establish new ones strategically to address regional challenges and diverse fish species. Encourage partnerships with international research institutions and organizations to share knowledge, access advanced technologies, and address global challenges like illegal fishing and transboundary resource management.

More specifically, the following research efforts need to be strengthened[5]:

- ***Sustainable fisheries management***: Balancing economic growth with environmental preservation to ensure a sustainable future for the fisheries sector.
- ***Technological advancements***: Developing and implementing innovative fishing, aquaculture, and post-harvest processing technologies to enhance efficiency and productivity.
- ***Resource efficiency***: Promoting resource-efficient aquaculture systems and practices to minimize environmental impact and maximize resource utilization.
- ***Ecosystem health***: Recognizing that fish and fisheries are part of a larger ecosystem, and managing them holistically to ensure the health and sustainability of the entire marine and freshwater environment.
- ***Post-harvest value addition:*** Promoting value-added processing of fish and other marine products to increase economic returns and create new opportunities.
- ***Market intelligence:*** Providing market intelligence and information to fishers and stakeholders to enable informed decision-making and optimize market access.
- ***Climate resilience:*** Developing climate-resilient fish species and culture systems to mitigate the impacts of climate change on fisheries.
- ***Data repository:*** Promoting the adoption of innovative technologies like remote sensing, data analytics, and underwater monitoring systems to improve stock assessment, resource management, and track illegal fishing activities.

[5] Drawn from Vision 2050 documents of various fisheries research institutions of ICAR.

5.2. Human resource development

5.2.1. Curriculum redesign and modernization

Introducing courses on emergent areas such as Blue Economy, Blue Transformation, climate change adaptation strategies for fisheries, cultivated fish meat and cloning, disruptive technologies like IoT, AI/ML, NLP, block chain technology, robotics, big data analytics, etc. as well as incorporating modules on sustainable fishing practices, responsible aquaculture techniques, ecosystem management, and certification & traceability within fisheries education programs need to be given a priority (ICAR, 2015a).

5.2.2. Multi-disciplinary approach

Creating a regional HRD consortium enabling seamless knowledge, capacity and facility sharing (with India as the hub), connecting the network of HRD institutions in India with the institutions in the South and South East Asian region would foster and strengthen collaboration between fisheries science with related fields like marine biology, environmental science, economics, and business management in the region to provide students with a holistic understanding of the sector. Facilitate student exchange programs with international institutions to promote knowledge sharing and adoption of best practices in fisheries education (GoI, 2020b).

5.2.3. Technology integration

Develop and utilize online learning platforms to provide students in remote locations with access to educational resources, recorded lectures, and interactive learning modules. To enhance student learning and engagement, equip classrooms with modern technology like virtual reality simulations, modelling tools, and data visualization software. Provide training on using technology relevant to the fisheries sector, such as GPS navigation systems, fish finders, and data analysis tools.

5.2.4. Capacity development and training

Organize capacity-building programs for existing faculty members to equip them with the latest knowledge on advancements in fisheries science, pedagogy, and effective teaching methods. Invite industry professionals to conduct guest lectures, workshops, and share their practical experience with students. Facilitate exchange programs for faculty members with international institutions to promote knowledge sharing and adoption of best practices in fisheries education.

5.2.5. Entrepreneurship development

Fishers and other stakeholders (both upstream and downstream) have not developed entrepreneurial skills as the sector has grown over time. The sector's activities and organization remain sticky and resist change. Steps need to be taken towards training, capacity building, and upgrading the technological skills of traditional fishers and fish farmers to move from artisanal fishing/farming to more economic and efficient means of carrying out their profession.

To fully gain from the benefits of commercializing fisheries and aquaculture, entrepreneurial skills of fishers and fish farmers will be developed, encouraging them to increase their reach in the fisheries value chain and other requirements of a modern fishery's sector. The Colleges of Fisheries established nationwide can play a role in this. Besides, some R&D institutions can also take up dedicated programs to build the entrepreneurship of stakeholders at different levels.

5.3. Reorient fisheries extension

Extension system in fisheries has certain unique features/challenges compared to crop and livestock sectors:

5.3.1. Delivering knowledge and extending technical support

India has one of the most extensive networks of fisheries R&D institutions in the world. The eight Fisheries Institutions under the ICAR umbrella; the six R&D Institutions under the MFAH&D, including a quasi-judicial body, the Coastal aquaculture Authority; three institutions under the Marine Products Export Development Authority; four Institutions under the Ministry of Earth Sciences; and the 40+ Colleges of Fisheries located in different States/UTs concerned with marine fisheries provide an unparalleled mass of experienced human resource for fisheries and aquaculture development in the country. Their coverage with respect to the disciplines and geography is extensive.

The fisheries Institutions of ICAR have been at the forefront of fisheries research and developmental initiatives since their establishment. Popularization of composite fish farming of the IMC and exotic species (silver carp, grass carp and common carp) and seed production technologies leading to the first 'Blue Revolution' in the country during the late seventies owes mainly to the extension services and hand-holding made available to fish farmers through the All India Coordinated Research Project of the ICAR and the setting up of the Fish Farmers

Development Agencies (FFDAs) by the then Ministry of Agriculture and Cooperation throughout the country. Similar developments occurred in farming air-breathing fishes, brackish water aquaculture and reservoir fisheries development. In the marine sector too, the ICAR Institutions are playing a stellar role, including the regular provision of marine fisheries data through a dedicated sampling methodology, setting benchmarks for the minimum-legal size of commercial species that can be harvested, stock assessments, completing the life-cycle of many commercially viable fish species for mariculture, five-yearly census of the marine fisheries sector, improved post-harvest technologies, new boat designs and quality control.

However, when major hikes are envisioned from the aquaculture sector, and capture fish production needs to be sustained at optimum levels, the expected role of the fisheries institutions assumes greater significance. Technologies that meet the immediate needs of the practitioners at the grassroots level are the need of the day. A balance between basic science and adaptive research is necessary. The need for extension services and hand-holding is felt much more than before. In other words, research should move ahead of development to absorb the outcomes in the developmental process, as it happened in the past. The R&D Institutions also have to forge a stronger relationship with the private sector and work in tandem to optimize the resources and shorten the technology transfer period from lab to land.

Knowledge dissemination up to the last mile will be one of the key objectives of the policy. With increasing literacy rates and the ever-increasing use of the internet and smartphones, knowledge dissemination will be primarily carried out through virtual platforms, making it fast and cost-effective and ensuring that no one is left behind. There is a need to establish IT-based knowledge 'hubs and spokes' for collecting, collating, and processing information that could be made available in real time to the fishers and fish farmers. It would also be ensured that such information provided to the end-users is in the vernacular so that assimilation becomes easier. In the marine sector, the provision of 'Sagar Mitras' promoted by the Department of Fisheries would be a valid contact point for the stakeholders.

6. Epilogue

The roadmap outlined in this document lays out an ambitious yet achievable vision to transform India's fisheries and aquaculture sector into a global leader in sustainability, innovation, and inclusive growth during the *Amrit Kaal* period, leading up to 2047. Guided by the principles of the Blue Economy, this comprehensive strategy aims to optimize the immense potential of India's aquatic resources through a harmonious balance between socio-economic development and environmental conservation. By prioritizing research and development, integrating cutting-edge technologies, and capacity building, the sector will be poised to achieve technological self-reliance, climate resilience, and competitive advantage on the global stage. Implementing this roadmap will not only bolster food and nutritional security for the nation. Still, it will also generate significant employment opportunities and drive inclusive socio-economic progress in coastal and rural communities. The emphasis on empowering small-scale fishers, women entrepreneurs, and youth will foster a more equitable and sustainable development trajectory. This vision underpins a strong commitment to ecosystem restoration, biodiversity conservation, and sustainable resource management. Through innovative approaches such as marine spatial planning, ecosystem-based fisheries management, and climate change adaptation strategies, India will emerge as a torchbearer for the responsible stewardship of its rich aquatic ecosystems. The successful realization of this roadmap hinges on collaborative efforts, forging strategic partnerships with diverse stakeholders, including research institutions, industry, civil society, and international organizations. By harnessing collective expertise and fostering a culture of evidence-based policymaking, India can effectively navigate the complex challenges and seize the opportunities that lie ahead.

7. References

DoF. (2020). National Fisheries Policy, 2020: Sixth draft for consideration (30 December 2020). https://dof.gov.in/sites/default/files/2020-12/Policy_0.pdf

FAO. (2020). Climate-smart fisheries and aquaculture (FAO eLearning Academy). https://elearning.fao.org/course/view.php?id=579

FAO. (2024a). The state of world fisheries and aquaculture 2024. https://www.fao.org/publications/fao-flagship-publications/the-state-of-world-fisheries-and-aquaculture/en

FAO. (2024b). The state of food security and nutrition in the world 2024. https://www.fao.org/publications/fao-flagship-publications/the-state-of-food-security-and-nutrition-in-the-world/en

GoI. (2020a). India's blue economy: A draft policy framework. Economic Advisory Council to the Prime Minister. https://incois.gov.in/documents/Blue_Economy_policy.pdf

GoI. (2020b). National Education Policy 2020. Ministry of Education. https://www.education.gov.in/sites/upload_files/mhrd/files/NEP_Final_English_0.pdf

ICAR. (2015a). *Vision 2050*: ICAR-Central Institute of Fisheries Education, Mumbai. https://www.cife.edu.in/hindi/pdf/Vision2050-CIFE.pdf

ICAR. (2015b). *Vision 2050*: ICAR-Central Marine Fisheries Research Institute, Kochi. https://eprints.cmfri.org.in/12729/1/CMFRI%2C%20ICAR%20%20-%20Vision%202050.pdf

ICAR. (2018). Handbook of fisheries and aquaculture (2nd ed.). https://icar.org.in/product/27

NAAS. (2016). Reservoir fisheries development in India: Management and policy options (Policy Paper No. 78). https://naas.org.in/Policy%20Papers/policy%2078.pdf

NAAS. (2024a). Food safety strategies for Indian fisheries sector (Policy Paper No. 125). https://naas.org.in/Policy%20Papers/policy%20125.pdf

NAAS. (2024b). Seaweed farming and utilisation (Policy Paper No. 127). https://naas.org.in/Policy%20Papers/policy%20127.pdf

UNDP. (2025). Future in focus: Preparing for what lies ahead 2025. https://desapublications.un.org/publications/future-focus-preparing-what-lies-ahead-0

World Bank. (2013). Fish to 2030: Prospects for fisheries and aquaculture (Agriculture and Environmental Services Discussion Paper No. 3). https://documents.worldbank.org/curated/en/458631468152376668

6 Natural Resources Management

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1. Introduction

Climate, land, soil, water, biodiversity, and forests constitute the natural resource base of agricultural production systems. Sustainable management of these natural resources is central to food, nutrition, environment and livelihood security of the nation and the planet. Soils are central to natural resource management, as soil processes support and regulate crop production, fresh water storage and quality, carbon storage, greenhouse gas (GHG) emissions, and several other ecosystem services. Sub-optimal agricultural practices can deplete or degrade soils, water, and climate resources and reducing their capacity to support crop production and other ecosystem services.

In India, the livelihood of ~50% of the population is directly dependent on agriculture. The agricultural food production system in India must provide food, feed, fodder, fiber, fuel, and furniture to the country that has the largest human and livestock population in the world and diverse needs. It is compounded further by climate change and associated global warming impacting all aspects of day-to-day existence. Government of India (GoI) has made several national and international commitments to achieve Sustainable Development Goals (SDGs). India's new commitments such as increasing the production of non-fossil fuel energy (500 GW by 2030); meeting 50% of energy requirements via renewable energy sources by 2030, reducing 1 billion tons of carbon emissions and carbon emission intensity of gross domestic product (GDP) by 45% by 2030 and restoring the degraded land and ultimately achieving the target of net zero emissions by 2070 (Srinivasa Rao *et al.*, 2021; 2024).

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Natural resources management (NRM) is, therefore, crucial for sustainable development, especially in a diverse and populous country like India. Among the myriad of natural resources available, soil and water are the most vital for agricultural sustainability, food security, and the overall health of the ecosystem. The effective management of these resources directly impacts agricultural productivity, farmer livelihoods, environmental health besides fulfilling the SDGs. Sustainable NRM is more critical for tropical ecosystems like India; where resources like soil-water-forest are under severe stress due to high pressure of human population and their food, fodder, fiber and other daily needs and also due to prevailing vulnerability of fragile ecosystems like high temperatures and coastal salinity. Natural resources vary spatially, soils even more so than others as they tend to have high site-specific constraints. This implies that, unlike seed-based technologies, NRM technologies e.g., technologies to improve soil and water productivity, tend to be highly site-specific. This requires that technology generation and transfer in NRM need to consider not only spatial variability of natural resources, but also the site-specific environmental and socio-economic constraints. These factors make stratification of spatially variable natural and environmental variables (particularly soils and climate) into relatively homogeneous spatial units a pre-requisite to NRM research and technology transfer.

Projected trends in food grain production, and natural use are presented in Table 1. The figures project the general trends rather than any definitive predictions. The actual outcome will be influenced by various factors, including government policies, technology adoption, climate change, market dynamics, and socio-economic factors.

Table 1. Projected trends in use of natural resources in India.

Parameter	2024	2030	2040	2047
Irrigated area (Mha)	115	125	135	140
Fertilizer use (Mt)	30	35	40	45
Food grain production (Mt)	332	360	400	450
Net cultivated area (Mha)	140	140	135	130
Food grain productivity (t ha^{-1})	2.4	2.6	3.0	3.5
Nitrogen use efficiency (%)	35	40	45	55
Surface water use efficiency (%)	35	40	50	60
Groundwater use efficiency (%)	45	50	65	75

India currently produces about 332 Mt of food grains annually. It is expected to increase to about 400 Mt by 2040 and reach upto 450 Mt aided by improved technologies, hybrid seeds and better crop management and protection technologies. Accordingly, productivity of food grains will increase from current 2.4 t ha^{-1} to 3.5 t ha^{-1} by 2047.

India has approximately 110 Mha of gross irrigated area. The GoI has a special focus on the development of irrigation resources, promoting micro-irrigation, and improving fertilizer use efficiency to meet the food requirement of the 1.64 billion population by 2047. Irrigated area is expected to grow around 135 Mha by 2040 due to investments in irrigation infrastructure, improved water management practices, implementation of new projects and making existing areas more efficient. By 2047 about 140 Mha will be under irrigation and shifting to improving irrigation efficiency with sustainable irrigation practices and policies.

Currently, India uses about 30 Mt of fertilizers annually, which is expected to reach around 40 Mt, reflecting increased crop demand and intensified agricultural practices driven by policies for promoting higher yields and shifting toward balanced fertilization. By 2047, it might stabilize at 45 Mt influenced by sustainability practices, focusing on efficiency.

2. Soil and Land Management

Soil and land are fundamental and finite natural resources. These need to be managed with care to sustain life on this earth. Land is basic support system for human life and development and top layer is generally viewed as soil; highly important towards agriculture and food production. Poor soil leads to poor quality of water, air and climate. Eventually, poor soil health results in poor health of plants, animals and humans and finally a poor society. If the Planet Earth is inhabited with humans and other life forms, it is because there is soil on it. Soil itself is a living system and is also a source of other lives. The health of soil, plant, animal, people, ecosystem and planet is closely inter-connected (Bolan *et al*., 2024), indivisible as One, and we should understand it as 'One Health'. One health of linking soil health to animal and human health was recently highlighted in G-20 deliberations in India. Soil provides a host of crucial services for people and the planet. It provides us food, ensures nutrition, cleans the water, purifies the air, protects us against floods, combats drought, mitigates climatic changes, and stores our heritage and culture. Soil security is the key to food, nutrition, energy, water and environment security. Soil management is also the key solution to climate change. Healthy soil is the base of a healthy society. And Sustainable Development Goals (SDGs) can be achieved only through sustainable and nature-friendly management of soil.

In the Green Revolution, soil management including the management fertilizer and nutrient played crucial roles in increasing productivity. A "Greener Revolution", therefore, can only be accomplished through judicious management of soil. Mismanagement of soil over the years, however, has deteriorated the health of soil. Indian soils are low on organic carbon and deficient in essential macro- and micronutrients. Soils are also getting degraded over the years. About 121 Mha of land of the country suffers from various forms of degradation.

2.1. Soil health and chemical inputs

Soil health is intricately linked with the use of fertilizers. While fertilizers are necessary for providing essential nutrients to crops, their excessive application without adequate soil health management can lead to negative consequences, such as reduced soil microbial diversity and increased susceptibility to pests and diseases. In India, the Green Revolution led to a dramatic increase in fertilizer usage, which initially boosted food production but has resulted in long-term negative soil health issues besides declining fertilizer use efficiency in food production. Fertilizers and other nutrient sources need to play a crucial role in enhancing crop production. However, nearly 50% of the applied nitrogenous fertilizers are leaked into the environment through volatilization, leaching or emissions causing adverse effects on terrestrial and aquatic systems and on human health. Efforts for enhanced use efficiencies of different nutrients through both improved crop varieties and management practices are continuously being made.

Thus, soil health plays a crucial role. However, soil degradation due to erosion, salinization, and nutrient depletion poses significant challenges. It is estimated that 30% of Indian soils are degraded. In addition to major nutrients, deficiencies of secondary nutrients like sulfur and several micronutrients e.g. zinc, boron, and iron are increasing. Intensive farming practices, coupled with the injudicious use of mineral fertilizers, have led to a decline in soil fertility, its partial factor productivity, and health over time. The overuse of fertilizers has led to a nutrient imbalance in the soil which causes adverse effects on crop yield and quality. Sustainable practices, such as integrated nutrient management, aim to balance soil nutrients through organic amendments and judicious use of mineral fertilizers (Srinivasa Rao *et al*., 2021b). This approach not only restores soil health but also enhances its capacity to retain water and nutrients, thereby promoting resilient agricultural production systems.

2.2. Managing land resources

Land resources are under increasing pressure from a variety of human activities. Sustainably intensifying land use is inevitable for food security of increasing population. However, soil degradation has become a major concern worldwide, with approximately 30-50% of the world's arable land affected by soil erosion and related processes. India has 121 Mha i.e., 36% of the geographical area degraded with soil erosion, salinity, alkalinity, acidity, water logging and other edaphic stresses (NAAS, Policy Paper No. 87, 2017, p. 14). To combat this, a combination of reclamation techniques and improved cultivation practices, supported by technological innovations and policy interventions is being implemented. Honorable Prime Minister at UNCCD (2019) announced the critical need and target of rehabilitation of 26 Mha of degraded lands to be rehabilitated by 2030 (NAAS Policy No 117. 2022; Pathak *et al*., 2023).

3. Water Management

Water is a vital and increasingly scarce commodity, particularly in a country where monsoon patterns are erratic and can significantly affect agriculture. India is one among top water stressed countries. India faces a pressing challenge with water management due to over-extraction from groundwater sources and inefficient irrigation management (Singh, 2019). Currently, agriculture consumes nearly 80% of India's freshwater resources, highlighting the urgent need for effective irrigation strategies. Despite having 4% of world's renewable freshwater resources, the country has only about 79 Mha under irrigation, and approximately 61 Mha dependent on rainfall. In the recent past, both drought and floods have increasingly stressed farming systems. India's annual replenishable groundwater potential is around 432 billion cubic metres (BCM), with over 90% of it already utilized in several regions. This overuse led to a sharp decline in groundwater tables, particularly in Punjab, Haryana, parts of Rajasthan, Gujarat, western Uttar Pradesh, and the Deccan plateau. Projected irrigation requirements are expected to reach at least 561 BCM by 2025 (against an availability of 784 BCM); and 628 BCM of 973 BCM by 2050 (Pathak and Ayyappan, 2020).

To address these challenges, adoption of water saving technologies like drip and sprinkler irrigation is crucial. Additionally, rainwater harvesting and improved farm water management practices can also play a significant role in ensuring a sustainable supply of water for agricultural use (Singh, 2022a). Effective water management not only enhances crop productivity but also builds resilience against the impacts of drought and climate change, which are becoming increasingly frequent across various parts of the country.

Addressing the water needs for agriculture in India by 2047 will require a multi-faceted approach involving innovative technologies, policy reforms, and active involvement from communities. It's essential to strike a balance between meeting agricultural demands and ensuring the sustainability of water resources for future generations. Collaboration among governments, farmers, and local communities will be critical to developing effective solutions. Seven important water management strategies and critical needs for sustainable water resources in Indian agriculture are discussed below.

3.1. Efficient irrigation practices

A shift from gravity irrigation to modern pressurized systems like drip and sprinkler irrigation enhances water-use efficiency (up to 90%) by minimizing losses through transpiration, evaporation, and runoff. Deficit irrigation involves applying water below full crop-water requirements, which can boost water productivity. Improved irrigation timing using climate-smart tools such as weather forecasting, hydrological monitoring, ICT, and agro-advisories enhances precision irrigation. Crop-specific methods like intermittent irrigation (alternate wetting and drying) are effective for improving water efficiency, reducing labor, and increasing yields. Micro-irrigation reduces the irrigation costs, energy consumption, and fertilizer usage by 20-50%, 31.0%, and 7-42%, respectively. It is further amenable to applying the water at the right time and the precise rate based on the crop's water requirement.

3.2. Water recycling and reuse

India's escalating water crisis highlights the urgent need for alternative water sources. Encouraging the reuse of treated wastewater for irrigation, especially in urban areas, to augment water supplies is the need of the hour. The reuse of treated wastewater offers a valuable solution to meet growing demands across sectors while easing pressure on freshwater supplies. India has the capacity to treat and reuse up to 80% of its wastewater. Utilizing treated wastewater in agriculture also helps conserve groundwater and reduces fertilizer usage due to its nutrient content.

3.3. Integrated water resources management

The principles of IWRM include integrating water and environmental management, adopting a systems approach, and ensuring full participation from all stakeholders, including communities and workers. It emphasizes social dimensions, capacity building, and access to reliable information for informed decision-making. Key elements also involve full-cost pricing with targeted subsidies, government support to create an enabling environment, use of best technologies and practices, sustainable financing, equitable water allocation, recognizing water as an economic good, and strengthening the role of women in water management. Moreover, implementing a holistic approach that coordinates the management of water, land, and related resources across sectors is needed to maximize social and economic welfare without compromising sustainability.

3.4. Watershed management

Watershed management serves as an effective water management strategy by promoting integrated planning and sustainable use of land and water resources within natural hydrological boundaries. It enhances water availability through *in-situ* measures like contour bunds and furrows, and ex-situ structures such as check dams and farm ponds, which improve soil moisture and recharge groundwater (Srinivasa Rao *et al*., 2022). Knowledge-based Entry Point Activities foster community involvement and ownership. Crop diversification, integration of farming systems, and capacity building reduce water demand and increase resilience. Participatory, consortium-based approaches ensure multi-stakeholder coordination while addressing equity, water rights, and conflict resolution. Overall, watershed management improves water efficiency, availability, and sustainability.

3.5. Groundwater management

Regulating groundwater extraction through scientifically informed policies is essential for ensuring sustainable use and aquifer recharge. Artificial groundwater recharge plays a crucial role in mitigating water scarcity, especially in arid and semi-arid regions where low rainfall limits natural infiltration. Combating groundwater depletion is a shared responsibility requiring coordinated action, grounded in equitable rights, clear responsibilities, and the adoption of innovative technologies.

3.6. Investment in water infrastructure

Investing in water infrastructure is vital for effective agricultural water management. This includes upgrading water supply systems, building reservoirs, and expanding canal networks. Empowering farmers through participation and access to credit encourages the adoption of suitable technologies, such as drip irrigation and decentralized rainwater harvesting. Farmer-based recharge structures and integrated surface micro-irrigation in canal areas improve groundwater sustainability and water productivity. Location-specific solutions, such as managing waterlogged lands and adopting water harvesting-based farming systems enhance resource efficiency.

3.7. Crop diversification with water efficient crops/systems

Promoting the cultivation of less water-intensive crops in areas facing severe water constraints will reduce overall water demand in agriculture. By growing a variety of crops with different resource requirements, farmers can optimize the use of water. This approach creates a buffer against dry conditions, ensuring better yield stability and reducing the need for excessive irrigation. Intercrops involving pulses, oil seeds and millets provides opportunity in effective utilization of surface and ground water resources (Srinivasa Rao *et al.*, 2016).

4. Tackling Climate Change

Climate is the key determinant of agricultural productivity. When climate fails, agriculture and consequently the economy suffers. Climate change is widespread and intensifying; rainfall variability and intensity are increasing; sea-levels are rising, and cyclones are becoming fiercer and frequent. Agriculture is one of the most vulnerable sectors, facing large scale impacts due to climatic changes. Atmospheric temperature, which has already risen by about 1.5°C, is rising consistently. The amount, variability, and frequency of extreme rainfall events (unseasonal rain, drought and flood) are rising while the duration of rainfall is reducing. Though regional impacts of climate change will vary, it is projected that yield of major crops would decline by 3-18% by 2040 under representative concentration pathway (RCP) 4.5 scenario. Considering the economic implication for agriculture food security and farmers' welfare, urgent adaptation and mitigation measures are required across various levels and scales.

India, endowed with favourable climatic conditions and rich agrobiodiversity, is considered one of the most vulnerable regions globally. Recent trends indicate rising and increasingly variable temperatures. These changes are expected to have negative impacts on the production of food grains, livestock and aquatic systems.

De-risking dryland agriculture from climate change should focus on production risks, business risks and external risks. However, different ecosystems such as arid, semi-arid, humic ecosystems need diverse technology for climate adaptation and mitigation of greenhouse gas (GHG) emissions (Nekoram *et al.*, 2023). These strategies need to be farmer-centric, participatory and region/sub-region specific. Farmers have to embrace climate smart agriculture centered around genotype x environment x management practices. A FARM-Building approach i.e., Foresee the stress (Forecasting), Adapt the stress (Adapting), Respond to the stress (Responding), Mitigate the stress (Mitigating) and Building capacity to manage the stress (Capacity building) needs to be implemented for resilient agriculture (Pathak, 2023). Various approaches, technologies and innovations that should be internalized are (1) genetic technology for developing climate resilient crop varieties; (2) early warning system of food insecurity in vulnerable districts and commodities; (3) managing water resources in rainfall excess/deficient hotspots; (4) developing alternate agriculture land use plans for resilient income growth and food security; (5) developing, and testing innovative, scalable, and inclusive insurance solutions; (6) setting up climate- and digitally-smart villages; (7) innovative partnerships for developing agriculture produce aggregation, storage and marketing models; (8) optimizing agriculture inputs and produce warehousing and distribution to minimizing losses and wastes; (9) developing an IT-based system for monitoring global and regional conflicts, food production and trade of relevance to Indian agriculture and trade and (10) developing an early warning system for real-time monitoring for key trans-boundary pests and diseases.

The management of natural resources plays a critical role in both adaptation and mitigation strategies concerning climate change and can effectively contribute to addressing these global challenges as described below:

4.1. NRM for mitigating GHG emissions

Natural resource management helps in reducing GHG emissions, which is essential for climate change mitigation. Some of the strategies are given hereunder.

4.1.1. Forestry and land use management

Forests and other ecosystems act as carbon sinks, absorbing CO_2 from the atmosphere. Sustainable forestry practices, reforestation, and afforestation can potentially enhance the soil carbon storage via carbon sequestration.

Likewise, managing land use to prevent deforestation and ecosystem degradation can effectively minimize GHG emissions from land-use change.

4.1.2. Agricultural practices

Implementing environmentally robust sustainable agricultural practices like agroforestry, cover cropping, and conservation tillage can significantly reduce GHG emissions from agricultural production by enhancing soil health and increasing carbon retention in the soil. Furthermore, improved management of livestock and feed practices can reduce methane emissions.

4.1.3. Wetlands as mitigation opportunity

Protecting and restoring wetlands helps sequester carbon, while also preserving biodiversity. Wetlands act as natural buffers against flooding, contributing to mitigation and adaptation.

4.2. NRM for climate change adaptation

Effective management of natural resources directly supports communities in adapting to the impacts of climate change. Key aspects include management of water, soil, cropping systems (Srinivasa Rao *et al*., 2020) as detailed further:

4.2.1. Adaptation through better water management

Efficient Usage: Strategies such as rainwater harvesting, improved irrigation systems, and watershed management help in conserving water resources, especially important in areas facing increased drought and water scarcity.

Flood Management: Proper management of river basins and floodplains can mitigate the impacts of flooding, which is becoming more frequent due to climate change.

4.2.2. Adaptation with better soil management

Healthy soils enhance agricultural resilience against extreme weather events like droughts and floods. Practices that maintain soil health, such as crop rotation and organic amendments improve water retention and reduce erosion.

4.2.3. Adaptation through diverse ecosystems preservation

Preserving ecosystems and maintaining biodiversity increases resilience to climate change impacts. Diverse ecosystems can better withstand and recover from climate shocks, providing essential services and resources for communities.

4.3. Agro-advisory and weather forecasting

Implementing advanced weather forecasting technologies and developing crop varieties that can withstand climate variability and water stress is essential towards climate change adaptation and co benefits of mitigation. Agromet Advisory Services at the district level supports farmers with real-time, weather-based insights for crop and livestock management. Integrating regional climate models like WRF with crop simulation models such as DSSAT enhances drought monitoring and yield loss assessment. This approach helps optimize water use, reduce risks, and improve productivity. With intensifying climate change, early-warning systems and localized advisories, including mobile apps in local languages, are essential for supporting resource-constrained regions.

5. Government Programmes for NRM

Effective governance and integrated natural resource management are key to support sustainability and resilience. The concept of 'new agriculture' advocates a more comprehensive approach, with regard to productivity, profitability and sustainability, across the entire value chain from farming to food, nutrition, health, environment, and employment. The focus is on farm production as well as farmers' income, towards which some of the recent governmental policies have stated the intent, as well as formulated schemes to enable them. The growing emphasis on both crop and animal-based farming, value addition, and techno-socio-economic tools such as Farmer Producer Organizations (FPOs), Agri-Startups, systems and practices aim to make agriculture both viable and sustainable. Foresight and partnerships that are knowledge-based and skill-oriented would be critical for farming as an enterprise, in order to build resilient and profitable production systems (Pathak and Ayyappan, 2020).

Creating awareness among stakeholders and showcasing the effectiveness of technologies for climate risk mitigation is essential for widespread adoption. Efficient agriculture, both on-farm and beyond-farm, would make farming a sustainable livelihood option, reducing distress migration from rural to urban areas. In this context, a 'seed-to-market' strategy anchored in innovation is crucial to curtail efficiency losses across the supply chain. With different kinds of stresses impacting farming, dimensions of speciality agriculture and secondary agriculture have to be incorporated, for a win-win for both the producer and the consumer. Transformational changes happening in all sectors of economy in a changing world have to be factored in for making farming 'smart' (Pathak and Ayyappan, 2020). Governments can strengthen climate action plans by embedding natural resource management within them, ensuring alignment between mitigation efforts and climate resilience. Actively involving local communities and incorporating Indigenous knowledge systems can significantly improve environmental stewardship and resource governance.

The Government of India has implemented several schemes aimed at promoting efficient water management, artificial groundwater recharge, improving soil health, and reducing reliance on mineral fertilizers. They are briefly described below:

5.1. Pradhan Mantri Krishi Sinchai Yojana (PMKSY)

The PMKSY is a flagship scheme launched by the GoI in 2015 to ensure coverage of irrigation ''Har Khet ko Pani'' and improving water use efficiency ''More crop per drop'' in an attentive fashion with end-to-end solution on source creation, distribution, and management. The scheme emphasizes the modernization of existing irrigation systems, water conservation practices, and the promotion of micro-irrigation technologies, such as drip and sprinkler irrigation.

5.2. Atal Bhujal Yojana (ATAL JAL)

Atal Bhujal Yojana was launched by the GoI in 2019 to improve groundwater management in the country through community participation. The scheme focuses on the sustainable management of groundwater resources by enhancing groundwater recharge, promoting efficient water use, and adopting water conservation practices. It encourages the participation of local communities in managing their water resources.

5.3. Soil Health Programme

Indian soils are hungry in terms of multiple nutrient deficiencies, and therefore nutrient inputs at right amounts synchronizing crop requirements is critical. However, excess amounts of fertilizer inputs particularly nitrogen leading to multiple issues of soil-water-environmental degradation. To combat these challenges, there is a growing recognition of the importance of soil health management practices. Promoting organic farming, adopting crop rotation, and utilizing bio-fertilizers can significantly improve soil fertility and sustainability. The Soil Health Card Scheme introduced by the GoI is a commendable initiative that aims to provide farmers with personalized reports on soil health, guiding them towards balanced fertilizer use and organic amendments.

The GoI launched the Soil Health Card (SHC) Scheme on February 19, 2015, to promote sustainable agricultural production systems by assessing the soil nutrient status and providing crop-specific recommendations to the farmers for balanced fertilizer use. Since 2022-23, the SHC scheme has been merged into the Rashtriya Krishi Vikas Yojana (RKVY) as one of its components (Soil Health and Fertility). The SHC provides information about 12 essential soil parameters i.e., macronutrients (N, P, K, S), micronutrients (Zn, Fe, Cu, Mn, B), and chemical parameters (pH, EC, and OC). The prime objective of the SHC scheme is to improve soil fertility, reduce excessive use of mineral fertilizers, and ensure long-term sustainability. The scheme also highlights digital integration, soil testing at three years, and empowering farmers by capacity building for making informed decisions about sustainable soil management. Furthermore, the SHC directly supports to NMNF (National Mission on Natural Farming) and PRANAM (Promotion of Alternate Nutrients for Agriculture Management) by guiding farmers about reduced use of mineral fertilizers, encouraging alternative and natural nutrient sources, and building healthy soils, which is imperative for natural farming.

5.4. National Mission for Sustainable Agriculture (NMSA)

The NMSA is one of the eight Missions under the National Action Plan on Climate Change (NAPCC) launched by the GoI to promote sustainable agriculture practices that enhance soil health and productivity. This mission includes five major components namely, 1) Rainfed Area Development; which promotes integrated and sustainable farming under rainfed areas, 2) Submission on Agroforestry to encourage tree plantation on farmland "Har Medh Par Ped", along with crops/ cropping system, 3) National Bamboo Mission (NBM) promotes quality bamboo cultivation, 4) Soil Health Management for balanced nutrient use by providing soil health card and promoting organic farming, and encouraging the use of bio-fertilizers and organic compost to reduce reliance on mineral fertilizers, and 5) Climate Change and Sustainable Agriculture: Monitoring, Modeling, and Networking (CCSAMMN), which support climate resilient agriculture through research, modeling, and bidirectional dissemination of climate change information tailored to local conditions.

5.5. Pradhan Mantri Fasal Bima Yojana (PMFBY)

The PMFBY is a comprehensive crop insurance scheme launched by the GoI to provide insurance coverage from sowing to the harvest stage to farmers against crop loss due to climatic aberrations, pests, and diseases. While primarily an insurance scheme, it also integrates aspects of sustainable farming by encouraging farmers to adopt better agricultural practices to reduce losses, including water conservation measures and improved soil management. By minimizing financial risk, PMFBY enhances resilience, supports rural livelihood and reinforces the country's commitments to SDGs.

5.6. National Agriculture Development Programme (NADP)

The NADP is a state-led, centrally supported strategic initiative to promote the holistic development of agriculture in the country. The program encourages practices that enhance sustainable agriculture, including rainwater harvesting, watershed development, and techniques for improving soil health. It empowers the States to design and implement region-specific, tailored programs focusing on crop diversification, mechanization, and value chain development so farmers can get an assured income. NADP also encourages entrepreneurship and market integration through support for agribusiness and value chain development.

5.7. Watershed Management Program (WMP)

The WMP is a holistic approach to conserving and developing natural resources like land, water and vegetation. The WMP is often implemented under national schemes like IWMP and PMKSY. The primary objective of WMP is to enhance the productivity of natural resources while ensuring ecological balance and sustainable livelihoods for rural communities, especially in rainfed and degraded regions. This program focuses on soil conservation, rainwater harvesting, recharging aquifers, and improving water quality and quantity through community participation. The program also emphasizes integrating allied livelihood activities like livestock horticulture, agroforestry, and micro-irrigation to support year-round income generation for small and marginal farmers.

5.8. Integrated Watershed Management Programme (IWMP)

The IWMP was launched in 2009-10, as a key initiative to restore ecological balance by harnessing, conserving, and developing degraded natural resources while improving farmers' livelihoods through allied activities and community participation. The program promotes strategies for groundwater recharge, soil conservation, and improving agricultural productivity while ensuring environmental sustainability. In 2015-16, IWMP merged into the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) as its Watershed Development Component (WDC-PMKSY). The program continues to play a pivotal role in addressing the resource degradation and climate change challenges in rainfed areas.

5.9. Paramparagat Krishi Vikas Yojana (PKVY)

The PKVY, a sub-component of the Soil Health Management (SHM) scheme under the National Mission of Sustainable Agriculture (NMSA), is a flagship scheme of the GoI launched in 2015. The PKVY scheme provides end-to-end support to organic farmers. The primary focus of the scheme is to form organic clusters (other than NE states) to help them create a value and supply chain with a robust focus on marketing. The scheme offers financial and technical support for cluster-based organic farming, certification under the Participatory Guarantee System (PGS), and capacity building and market linkage. The scheme aims to promote natural resource-based, integrated, and resilient farming systems that improve soil fertility, conserve natural resources, and encourage on-farm nutrient recycling while minimizing farmers' dependence on external inputs. The PKVY also aims to reduce the cost of production and ensure the effective production of nutritious foods without compromising the soil and environmental quality.

5.10. Namami Gange Programme

The Namami Gange Programme, launched in 2014 by the GoI as a flagship initiative for the rejuvenation of the River Ganga, aims to achieve the twin objectives of effective abatement of pollution and conservation and rejuvenation of the Ganga. Sewage treatment, riverfront development, River surface cleaning, industrial effluent monitoring, biodiversity, afforestation, public awareness, and Ganga Gram are the main pillars of this program. Initiatives like sewage treatment, solid waste management, and river surface cleaning, indirectly support better water management practices in agriculture along river basins. In addition, a corridor of 5-7 km along the banks of the Ganges is under development for organic farming so that the pollution of the Ganges water due to the use of fertilizer and pesticides by farming on its banks is prevented. Besides that, tree planting along riverbanks and micro-irrigation is also promoted under the program to minimize runoff and wastage of water in the Ganga villages.

5.11. PM-PRANAM (Promotion of Alternate Nutrients for Agriculture Management)

The scheme was announced in the Union Budget of 2023-24 to reduce mineral fertilizer use by rewarding states that promote alternate fertilizers. The scheme also supports NMNF because natural farming requires minimal or zero chemical input and makes the transition financially attractive for states and farmers. It also meets PRANAM's target of cutting chemical fertilizer usage.

5.12. PM-Prakritik Krishi Yojana (PM-PKY)

The PM-PKY is a central government scheme launched in 2022 to promote cost-effective and environmentally robust natural farming practices across India, especially along the Ganga River basin and other vulnerable ecological zones. The scheme aligns with the vision of sustainable agriculture, soil health conservation, and environmental protection. The scheme supports farmer capacity building, the creation of input resource centers, and participatory certification systems to ensure trust in natural produce. Furthermore, PM-PKY directly contributes to the Namami Gange Programme by reducing chemical runoff into the River Ganga. It promotes natural farming in Ganga Grams, thus helping in pollution reduction and ecosystem restoration. Overall, by PM-PKY, India can potentially shift towards regenerative agricultural production systems that enhance food security, farmer income, and ecological balance while supporting the country's national and international commitments.

6. Policy and Governance of NRM: Critical Needs

6.1. Water pricing and subsidies

Reforming water pricing for agriculture is essential to promote conservation while ensuring small farmers have affordable access. Effective pricing supports sustainable water management, equity, and reliable service. Strengthening Water Regulatory Authorities across states can ensure fair and transparent pricing. Gradually implementing volumetric pricing in well and tube-well-irrigated areas, supported by investments in measurement infrastructure, is crucial. In the interim, crop-area-based pricing should be simplified and revenue collection should be improved. Groundwater use must be regulated through appropriate rural power tariffs and a Groundwater Conservation Fee (GWCF). A rational, inclusive, and regularly reviewed pricing framework is vital to ensure sustainable and equitable water use in India.

6.2. Legal framework for water rights

Establishing clear and fair legal frameworks regarding water rights will prevent conflicts among users and promote equitable distribution. The Model Groundwater (Sustainable Management) Act, 2016, and

Groundwater Act, 2011 treat groundwater as a public good, reflecting a shift away from private ownership. These laws aim to prevent over-extraction, pollution, and degradation, supporting sustainable groundwater use. Under the Environment Protection Act, the Central Ground Water Authority regulates industrial use and extraction. Despite states having primary control over water, central initiatives like the River Basin Management Bill (2019) and Dam Safety Authority Bill (2019) indicate a shift towards centralized regulation. However, such top-down reforms may not fully address issues, such as safe drinking water, sustainable irrigation, and ecological impacts, especially from large dams and river interlinking projects. Going forward, future reforms must focus on creating an inclusive, socio-legal framework that integrates traditional knowledge, scientific input, and human rights, ensuring equitable and sustainable access to water, particularly in agriculture.

6.3. Decentralized water governance

Strengthening local governance structures and community participation in water management is essential to ensure more tailored and effective approaches to local conditions. Decentralized water governance, through empowered gram panchayats and active village communities, is vital for sustainable and inclusive water management in India. Empowering gram panchayats with financial autonomy, technical skills, and converged resources is essential. The rural-urban divide can be bridged through local-source-based water systems, which are more cost-effective and sustainable. Decentralization must be rooted in community empowerment, active gram sabhas, and the recognition of nature's limits, making village-level institutions the cornerstone of India's long-term water security.

6.4. Research and development

Investing in R&D for innovative agricultural practices, crop varieties, and water-efficient technologies will develop technologies to enhance resilience against water scarcity. Government initiatives like ICAR's NICRA promote climate-resilient technologies and drought-tolerant crops. Programs like NePPA use ICT, robotics, and data analytics for precision agriculture (Singh, 2022b), while AICRP-IFS and AINP-OF develop sustainable and organic farming models. The NMSA, under NAPCC, focuses on rainfed area development, soil health, and water management, complemented by insurance schemes like PMFBY. These efforts ensure sustainable agriculture, improved livelihoods, and long-term water resource conservation in a climate-challenged future.

6.5. Public awareness and education

Raising awareness about water conservation and sustainable agricultural practices is crucial for ensuring long-term water security and environmental sustainability. Public awareness campaigns, including social media outreach, community events, and workshops, play a key role in educating individuals about the importance of water-saving practices such as rainwater harvesting, efficient irrigation, and reducing water wastage. Education programs integrated into school curricula and community outreach, including field trips and interactive workshops, further empower people to make informed choices. Additionally, engaging in policy advocacy, stakeholder engagement, and capacity building enhances the impact of water conservation efforts.

6.6. Climate friendly policies

Integrating climate change mitigation and adaptation strategies into water management policies is essential for building resilience in India's agricultural systems. Adaptation strategies such as upgrading infrastructure, enhancing water conservation practices, and implementing nature-based solutions can help farmers and communities cope with immediate climate impacts. Mitigation efforts, including reducing GHG emissions and improving carbon sequestration in soils will ensure long-term sustainability. By fostering partnerships and updating policies, India can enhance climate resilience, secure water resources, and contribute to global climate goals while ensuring food security and meeting the Sustainable Development Goals (SDGs), especially SDG 6 (Clean Water and Sanitation).

6.7. Institutional framework

Enhancing coordination among various government departments and agencies involved in water management for agriculture is important to streamline efforts and avoid duplication of initiatives. Strengthening inter-agency coordination, clarifying roles, and fostering communication among institutions like the Irrigation, Water Resources, and Public Health Engineering Departments is crucial for efficient water use. Additionally, empowering local bodies such as Panchayati Raj Institutions (PRI) and water user associations will promote sustainable groundwater governance and equitable water distribution, helping mitigate India's water scarcity challenges.

6.8. Need for a comprehensive approach

To meet the diverse requirements of food, fiber, fuel, feed, and fodder in India by 2047, a comprehensive approach involving research, innovative management strategies, and robust policy support is essential. Engaging stakeholders, from farmers to policymakers, will be critical in developing and implementing effective solutions that balance resource sustainability with socio-economic growth. These are briefly described here:

7. Recommendations

7.1. Researchable issues

7.1.1. Sustainable agricultural practices

- Investigating the impact of agroecological practices on soil health and crop productivity.
- Assessing the viability of organic farming and its scalability across different regions.
- Developing appropriate conservation agriculture (CA) technologies for various farming contexts, addressing challenges with smallholders and integrating CA with other farming practices.

7.1.2. Climate change adaptation

- Researching impacts of climate change on crop yields and natural resources.
- Developing climate-resilient crop varieties with improved drought and flood tolerance.

7.1.3. Water resource management

- Analyzing groundwater depletion and its socio-economic impacts.
- Exploring advanced irrigation technologies and their cost-effectiveness.
- Developing more effective soil and water erosion control practices and predicting erosion rates under changing climate.

7.1.4. Soil health management

- Studying the relationship between soil fertility, crop productivity, and socio-economic factors.
- Assessing the long-term effects of chemical fertilizers versus organic amendments.

7.1.5. Biodiversity conservation

- Researching ways to preserve traditional crop varieties and livestock breeds.
- Evaluating the role of agro-biodiversity in enhancing ecosystem resilience.

7.1.6. Energy sources in agriculture

- Investigating alternative energy sources for agricultural operations, including biogas and solar energy.
- Assessing the integration of regenerative energy practices in farming like photovoltaics.

7.1.7. Waste management

- Developing techniques for converting agricultural waste into valuable resources (e.g., biofuels, compost).
- Exploring the role of circular economy in agricultural practices.

7.2. Management Strategies

- ***Integrated resource management***: Implementing a systems approach to manage soil, water, and biodiversity together for designing sustainable agricultural practices.
- ***Adoption of technology and innovation***: Promoting precision farming technologies to enhance resource use efficiency and crop management. Utilizing mobile technology and data analytics to inform farmers about optimal practices and market trends.
- ***Promoting agroforestry***: Encouraging the integration of trees into agricultural landscapes to enhance productivity, provide fodder, and improve carbon sequestration.
- ***Enhancing extension services***: Strengthening agricultural extension systems to disseminate knowledge on sustainable practices and technologies among farmers.
- ***Resilience building***: Developing community-based disaster risk reduction strategies to protect livelihoods against climate-induced shocks.
- ***Market access and support***: Facilitating better market access for farmers through cooperatives and value chains that incorporate fair pricing for sustainable practices.

- ***Livelihoods diversification*:** Promoting alternative income-generating activities, such as agro-tourism or handicrafts, to reduce dependence on traditional agriculture.

7.3. Policy support

- ***Subsidies and incentives*:** Implementing targeted subsidies for sustainable practices, such as organic farming, and technologies like drip irrigation.
- ***Water management policies*:** Formulating policies to promote comprehensive water conservation strategies, including rainwater harvesting and groundwater recharge.
- ***Land use regulations*:** Establishing policies that prevent land degradation and encourage sustainable land use, including zoning laws for agricultural land.
- ***Research and development funding*:** Increasing public and private investment in agricultural research to promote innovations that address resource management challenges.
- ***Skill development*:** Developing training programs for farmers on sustainable practices, resource management, and business skills.
- ***Environmental regulations*:** Strengthening environmental protections to mitigate the impacts of agricultural activities on ecosystems and biodiversity.
- ***Intersectoral collaboration*:** Fostering collaboration among various ministries (e.g., agriculture, environment, energy) to create cohesive policies that address the complexities of resource management.

8. Epilogue

The sustainable management of natural resources such as soil, water, climate, and biodiversity in India is imperative for achieving food security, enhancing farmers' income, and ensuring ecological balance. By prioritizing natural resource management, India can work towards a sustainable future that supports its large population while preserving the environment for generations to come. The management of natural resources is also a cornerstone for both adapting to and mitigating the impacts of climate change. By enhancing carbon sequestration, promoting sustainable agricultural and water management practices, and preserving ecosystems, effective resource management not only addresses the immediate threats posed by climate change but also contributes to overall ecological health and resilience. As India progresses towards more sustainable agricultural practices, the integration of effective soil and water management strategies will be the key to ensuring a secure and prosperous future.

9. References

Bolan, N. S., Srinivasa Rao, Ch., Rocco, C., Bolan, S., Mansoor, S., Wani, O. A., *et al*. (2024). Zinc in soil–crop–animal–human health continuum. Advances in Agronomy. https://doi.org/10.1016/bs.agron.2024.09.004

National Academy of Agricultural Sciences (NAAS). (2022). Road map for rehabilitation of 26 Mha degraded lands in India (Policy Paper No. 117). New Delhi: NAAS.

Naorem, A., Jayaraman, S., Dang, Y. P., Dalal, R. C., Sinha, N. K., Srinivasa Rao, Ch., & Patra, A. K. (2023). Soil constraints in an arid environment – Challenges, prospects, and implications. Agronomy, 13, 220, 1–29.

Pathak, H. (2023). Impact, adaptation and mitigation of climate change in Indian agriculture. Environmental Monitoring and Assessment, 195, 52–74. https://doi.org/10.1007/s10661-022-10537-3

Pathak, H., & Ayyappan, S. (2020). Sustainable agriculture in a changing world. Current Science, 119, 1731–1732.

Pathak, H., Srinivasa Rao, Ch., & Jat, M. L. (2021). Conservation agriculture for climate change adaptation and mitigation in India. Journal of Agricultural Physics, 21(1), 182–196.

Singh, A.K. (2019). Water management - Is quantum or negligence - the issue? Indian Journal of Fertilisers, 15, 836-847.

Singh, A.K. (2022a). Water management technologies / strategies to make India food and nutrition secure by 2050. Indian Journal of Fertilisers, 18, 1258-1277.

Singh, A.K. (2022b). Precision agriculture in India - opportunities and challenges. Indian Journal of Fertilisers, 18, 308-331.

Srinivasa Rao, Ch., Gopinath, K. A., Prasad, J. V. N. S., Prasannakumar, & Singh, A. K. (2016). Climate resilient villages for sustainable food security in tropical India: Concept, process, technologies, institutions, and impacts. Advances in Agronomy, 140(3), 101–214.

Srinivasa Rao, Ch., Pathak, H., & Dwivedi, B. S. (2024). Agriculture sector contributions in achieving net zero emission by 2070 (Policy Paper No. 13). ICAR-National Academy of Agricultural Research Management, Hyderabad.

Srinivasa Rao, Ch., Prasad, J. V. N. S., Rao, K. V., Kiran, B. V. S., Ranjit, M., Girija Veni, V., Priya, P., Abhilash, P. C., & Chaudhari, S. K. (2022). Land and water conservation technologies for building carbon positive villages in India. Land Degradation & Development, 33(3), 395–411. https://doi.org/10.1002/ldr.4160

Srinivasa Rao, Ch., Rakesh, S., Ranjith Kumar, G., Manasa, R., Somashekar, G., Subha Lakshmi, C., & Kundu, S. (2021). Soil degradation challenges for sustainable agriculture in tropical India. Current Science, 120(3), 492–500.

Srinivasa Rao, Ch., Rao, K. V., Gopinath, K. A., Prasad, Y. G., Arunachalam, A., Ramana, D. B. V., Ravindra Chary, G., Gangaiah, B., Venkateswarlu, B., & Mohapatra, T. (2020). Agriculture contingency plans for managing weather aberrations and extreme climatic events: Development, implementation and impacts in India. Advances in Agronomy, 159, 1–43. https://doi.org/10.1016/bs.agron.2019.08.002

Srinivasa Rao, Ch., Singh, S. P., Kundu, S., Abrol, V., Lal, R., Abhilash, P. C., Chary, G. R., Thakur, P. B., Prasad, J. V. N. S., & Venkateswarlu, B. (2021). Integrated nutrient management improves soil organic matter and agronomic sustainability of semiarid rainfed Inceptisols of the Indo-Gangetic Plains. Journal of Plant Nutrition and Soil Science, 184(6), 1–11. https://doi.org/10.1002/jpln.202000312

7 Farm Mechanization

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1. Context

India's diverse agroecological landscape encompasses a broad spectrum of climatic zones, physiographic conditions, soil types, hydrological resources, and solar radiation, all of which contribute to its substantial potential for agricultural development. The strategic vision under Amrit Kaal 2047 emphasizes the advancement of a high-productivity, resource-efficient, and climate-resilient agricultural system. This includes optimizing water and nutrient inputs while mitigating climate change, land degradation, and ecological stress challenges.

Farm machinery encompasses the complete range of mechanical tools, implements, and equipment employed in pre-production, production, post-harvest handling, and on-farm processing of agricultural commodities, including crops, livestock, poultry, and aquaculture. An effective developmental roadmap should incorporate a dynamic matrix that evaluates both present limitations and anticipated future needs, shaped by climatic variability, farm typologies, market trends, input availability, and food demand trajectories.

Mechanization requirements depend on various biophysical and socioeconomic parameters, including landholding size, soil characteristics

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(physical, chemical, and biological), agroclimatic conditions, cropping and livestock systems, input accessibility (e.g., seeds, fertilizers, irrigation, agrochemicals), produce perishability, logistical infrastructure, and market demands. A systematic appraisal of the current status and forward-looking requirements for agricultural machinery is essential to support a paradigm shift toward sustainable and climate-adaptive farming systems.

2. Present Status

2.1. Farm power availability

Approximately 47% of agricultural operations in India are mechanized, significantly lower than levels observed in comparator nations such as China (60%) and Brazil (75%) (Rao, 2024). The mechanization process gained momentum during the Green Revolution of the 1960s, which emphasized high-yielding varieties (HYVs), irrigation intensification, and nutrient supplementation. The adoption of tractors played a pivotal role in enhancing the efficiency of field operations, particularly for tillage and irrigation.

Tractors presently constitute approximately 80% of the agricultural machinery market in India. According to the Investment Information and Credit Rating Agency (ICRA), in 2023, tractor sales reached a record 950,000 units, with an estimated 4.3 million units operational by mid-2024 (ICRA, 2024). Despite this expansion, the lack of a comprehensive, empirical survey on the supply and demand of agricultural machinery impedes strategic planning.

Farm mechanization is typically assessed through farm power availability (kw/ha), which includes mechanical, electrical, human, and animal power (Mehta *et al*., 2019). This indicator has increased from 0.28 kW/ha in 1960–61 to 2.761 Kw/ha in 2020–21. The area serviced per tractor has declined substantially from 36 ha per unit to approximately 14 ha per unit, indicating increased accessibility and deployment (Mehta *et al*., 2023).

2.2. Cropping intensity

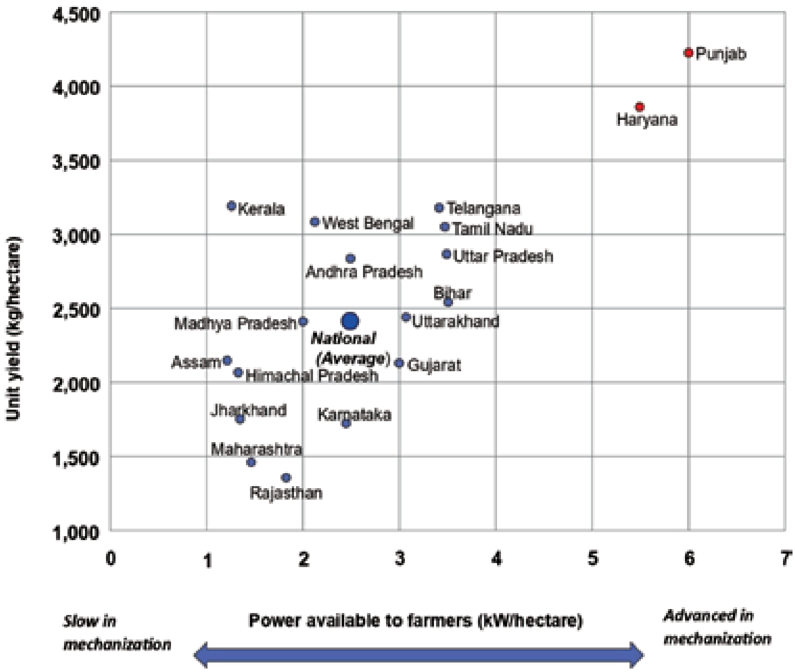
Cropping intensity, a key indicator of land-use efficiency, increased from 114% in the 1960s to approximately 140% in 2015. However, this increase does not correspond proportionally with the expansion in mechanized land area. Water availability and timely input application remain the principal determinants of cropping intensity. Technological interventions such as rainwater harvesting, micro-irrigation, and alternate wetting and drying (AWD) methods have demonstrated efficacy in enhancing cropping intensity, with modest improvements noted over the past two decades.

2.3. Yield and power correlation

According to the World Bank (2022), cereal yield in India was 3,567 kg ha^{-1}, markedly lower than the yield reported in the United States (8,072 kg ha^{-1}). Notably, the U.S. yield in 1973 was comparable to current Indian levels (3,683 kg ha^{-1}), suggesting that long-term investment in seed technology, fertilization, crop protection, and mechanization has played a transformative role in enhancing productivity.

There exists a demonstrable positive correlation between farm power availability and agricultural yield. Sufficient power availability enables the timely execution of critical operations such as seedbed preparation, sowing, interculture, irrigation, and harvesting. Historical data from 1961 to 2021 (Figures 1 & 2) indicate a linear increase in food grain

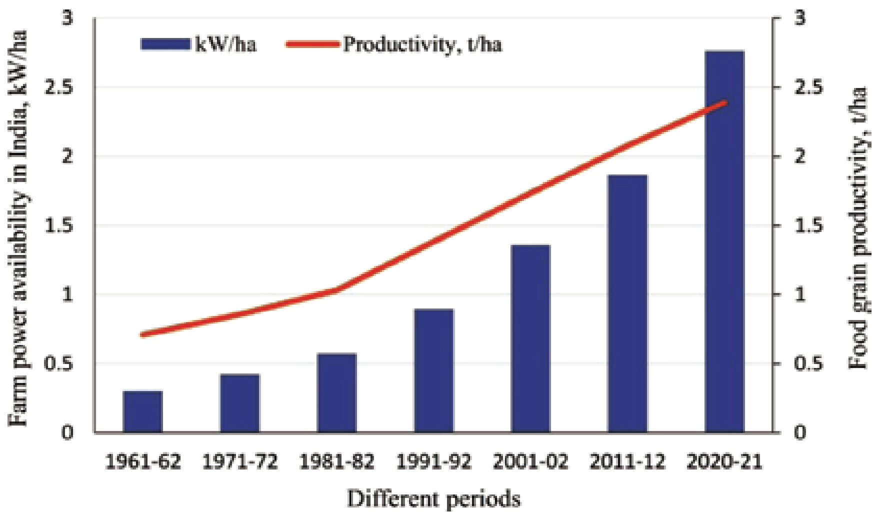
Figure 1. *State-wise relationship between power availability and yield.*



Source: *Compiled by MGSSI based on data of India's Ministry of Agriculture & Farmers Welfare*

*Data for mechanization of agriculture are for FY 2018-2019; data for unit yield of food grain crops are for FY 2021-2022.

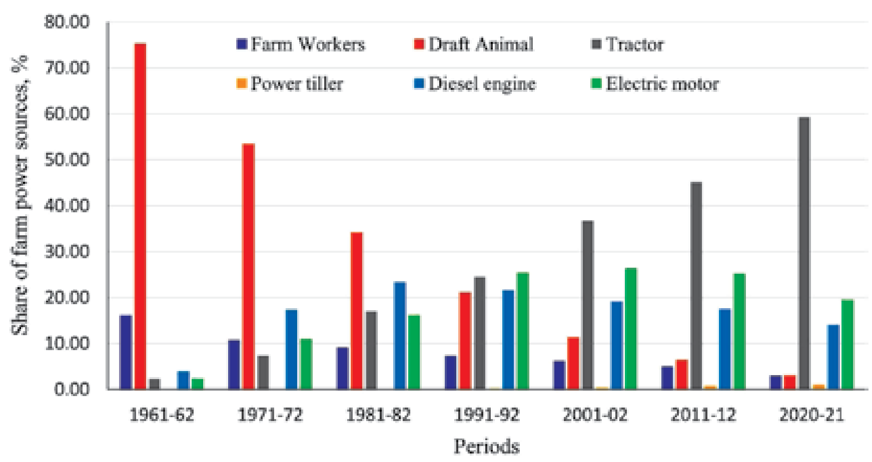
Figure 2. *Farm power availability and food grain productivity during 1961-2021.*



productivity (from 0.71 to 2.39 t ha^{-1}) corresponding to a rise in power availability from 0.3 kw/ha to 2.76 kw ha^{-1} (MOA&FW, 2018 and Anon, 2015).

The structural composition of farm power (Figure 3) reveals a transition from traditional animal-based sources to modern mechanical power. Between 1961–62 and 2020–21, the share of mechanical power increased over 110-fold. The contribution of tractors and power tillers rose from

Figure 3. *Changing composition of farm power on Indian farms from 1961 to 2021.*



38% to 81%, while human and animal sources declined from over 90% to approximately 6%. Electrical power increased from 2% to 20%, reflecting broader electrification and pump adoption.

Mechanization in cereal cultivation accounts for 60% of land preparation, 40% of seeding, 50% of plant protection, 45% of irrigation, and 70% of harvesting. Tractors (30–50 HP range) are widely used for haulage and operational efficiency. However, mechanization remains underutilized in non-cereal crops such as cotton and sugarcane (Rao, 2024).

Increasing mechanization does not necessarily entail high capital investment. Critical is selecting context-specific power sources based on scale, function, and resource availability. With over 80% of Indian farmers categorized as small or marginal, affordability remains a key constraint. In states such as Punjab and Haryana, the deployment of Custom Hiring Services (CHS) has proven effective in bridging this gap (Yukiko, 2024).

3. Current Challenges

The central challenge is to enhance the profitability, dignity, and sustainability of farming to attract and retain youth in the agricultural sector (Sansad, 2023; NITI Aayog, 2018). Mechanization is critical in addressing the emerging constraints posed by climate change, soil degradation, agrochemical overuse, environmental degradation, and labor shortages, particularly in labor-intensive crops and allied sectors (GOI, 2022; Trendov, 2019).

Key mechanization challenges include:

- ***Soil health restoration*:** Development and dissemination of conservation agriculture equipment, including zero-tillage seeders and in-situ residue management tools for smallholder systems.
- ***Input use efficiency*:** Precision application technologies for fertilizers and agrochemicals, including variable-rate and targeted spraying systems (e.g., laser-guided sprayers, "See and Spray" systems).
- ***Post-harvest management*:** Mechanized harvesters, decentralized storage solutions, and improved cold-chain logistics to reduce post-harvest losses.
- ***Water productivity*:** Automation of irrigation and fertigation using AWD and sensor-based scheduling.
- ***Allied sectors*:** Mechanization in animal husbandry, poultry, and fisheries to enhance productivity and reduce labor intensity.

- ***Natural resource management*:** Equipment for land reclamation (e.g., saline soils), agroforestry, and watershed interventions.

4. Current Requirements

As one of the world's largest producers and exporters of tractors, India is expected to sustain a 3–5% CAGR, with future growth concentrated in high-tech, crop-specific, and export-oriented models. Given improved rural connectivity, the reliance on tractors for transportation is expected to decline.

The expansion of CHCs is crucial to popularize access to advanced mechanization. Tractors with modular, multi-operation implements suitable for CHC deployment are expected to increase. To facilitate this, policy should reorient capital subsidies away from individual ownership toward CHC-based procurement. Individual farmers could instead receive service-based subsidies, which are outcome-driven and equitable.

Subsidies should be restricted to domestically manufactured small implements to strengthen the domestic machinery ecosystem, particularly among MSMEs. The import of subsidized small machinery from countries such as China undermines local manufacturing capacity. Given acute labor shortages and their strategic value, sugarcane and cotton mechanization should be prioritized. Comparative analysis reveals that the U.S. achieved 100% mechanization of cotton in 30 years, while Turkey reached 75% mechanization within 15 years, driven by labor economics, agronomic compatibility, and targeted policy support.

5. Agricultural Machinery Industry

The agricultural machinery sector, particularly the tractor industry, plays a critical role in India's farm modernisation strategy. In 2023, India produced and sold approximately 1.01 million tractors, with 10% directed to export markets. The sector is projected to grow at a 5% CAGR. Currently, about 45% of tractors are used primarily for land preparation and some for harvesting.

Government schemes such as the Pradhan Mantri Kisan Tractor Yojana and NABARD's mechanization programs provide purchase-based subsidies (up to 50% for tractors and 100% for transport implements). However, these schemes often exclude smallholders due to affordability issues. CHCs help address this gap, though many face financial burdens from high maintenance and upgrade costs.

A transition to service-based subsidy models is recommended. These would fund mechanization rather than ownership, enabling CHCs to invest in advanced, interoperable technologies and improving machinery utilization rates by up to 25%. Monitoring services can be facilitated using geospatial technologies, drones, and satellite imagery.

Indian tractors are technologically lagging due to cost constraints. Many features, such as ISO Bus interfaces and modern safety mechanisms, are offered only in export models. A shift to service-based subsidies would incentivize manufacturers to innovate for domestic markets and produce advanced attachments for crop-specific operations (e.g., sugarcane transplanters, cotton harvesters).

Certainly. Here is a critically proofread and refined academic version of your content, with enhanced clarity, coherence, formal language, and consistent structure. The tone is more analytical, and phrasing has been improved to meet academic and technical standards.

5.1. Strengthening agricultural machinery testing infrastructure

The pace of agricultural machinery testing in India requires substantial acceleration (MOAFW, 2018). Anecdotal evidence from manufacturers indicates that, over the past two years, a prominent Indian testing center evaluated approximately ten imported combine harvesters, while no such tests were conducted for machines manufactured domestically. This reflects a concerning imbalance in testing priorities and highlights the need for policies that support indigenous manufacturers through reduced testing costs and equitable access. Expanding the network of certified testing centers is imperative to facilitate timely evaluations, which are critical for the rapid commercialization of domestically produced agricultural machinery.

5.2. Promotion of crop varieties compatible with mechanization

The effectiveness of agricultural machinery is intrinsically linked to the crops' physical uniformity and maturity synchronization. India's limited mechanization in key crops such as sugarcane, cotton, and soybean is largely attributable to varietal characteristics that hinder efficient mechanical operations. For instance, cotton harvesting is complicated by asynchronous boll maturation, requiring multiple manual plucking rounds. In sugarcane, parameters such as plant spacing and stalk height are critical for mechanized harvesting. Soybean cultivation faces challenges due to low ground clearance, which restricts mechanized operations. Although suitable crop varieties addressing these mechanization needs do exist, their dissemination and adoption remain inadequate. Manual harvesting operations, such as cotton picking, contribute up to 30% of total cultivation costs. Given rising labor costs and scarcity, a coordinated effort involving plant breeders, agronomists, and mechanization experts is essential to identify, develop, and promote crop varieties amenable to mechanical operations.

5.3. Advancing agricultural technology and input efficiency

Agriculture in India accounts for 80–90% of freshwater use and exhibits inefficiencies in fertilizer and agrochemical applications, with less than 10% effective uptake. While micro-irrigation systems (e.g., drip and sprinkler) have been subsidized and moderately adopted, the next frontier involves automating input delivery for enhanced efficiency and sustainability. Promoting small and medium enterprises engaged in agricultural electronics and automation is vital. Currently, many subsidized polyhouses remain underutilized due to the absence of affordable climate control technologies. Financial incentives—such as low-interest credit lines and tax exemptions—should be extended to tech-driven agri-startups. Technologies warranting support include precision application systems, guidance and navigation tools, robotics, and automation. Furthermore, energy efficiency remains a critical concern. For example, irrigation pumps currently operate at 30–50% efficiencies. Companies working on energy-efficient agricultural machinery should receive targeted support to address this systemic inefficiency.

6. Research and Development Priorities in Farm Machinery and Mechanization

6.1. Tractors

The Indian tractor market is characterized by high capital intensity, low utilization rates—especially among smallholders—and limited adaptability for multi-functional roles. Diesel-powered tractors dominate the market, although biofuel and electric alternatives are emerging. Current applications include tillage, seeding, fertilization, irrigation, harvesting, and transport. The future trajectory envisions the transition toward semi-autonomous and autonomous tractors, which will function as versatile power units interfacing with a variety of implements. The rise of modular, small-scale autonomous machines capable of collaborative operations with different attachments is also anticipated. This paradigm shift will redefine tractors not merely as tillage machines, but as integral components of fully mechanized and automated farm ecosystems.

6.2. Self-propelled machines

At present, self-propelled machines such as rice transplanters and combine harvesters are limited in scope and predominantly utilized in large-scale cereal production. Their operational windows are narrow, often restricted to a few weeks per season. Custom-hiring models have partially facilitated access for smallholder farmers. However, significant research and development are required to design compact, multi-crop adaptable self-propelled machinery, particularly for horticultural and fibre crops. Many of these machines are in the early research or prototype phase and require accelerated development and field validation.

6.3. Drones and robotics in agriculture

Drones are increasingly used for foliar application of agrochemicals, including nano-urea, though technical shortcomings such as inadequate nozzle design and directional control limit efficacy. Application losses are especially pronounced in crops with sparse canopies. Robotic technologies in Indian agriculture remain in the exploratory stage, with significant constraints including high capital costs, limited battery life, inadequate operator training, and issues related to wind drift and data integration. Despite these challenges, drones exhibit substantial potential in areas such as crop monitoring, yield estimation, disease prediction, terrain logistics, and precision input application. Most drone-based and robotic solutions are currently at prototype or research stages and require targeted support to achieve commercial scalability (FAO and ZJU, 2021).

6.4. Tillers, cultivators and weeders

There is a need to revisit the technical standards and economic models governing tillage and weeding implements. The promotion of domestically manufactured cultivators with low soil compaction footprints is essential. Emerging technologies such as laser-based non-tillage weed control merit focused research. Although power tillers are compatible with various attachments, weeding remains labor-intensive and physically demanding, especially in undulating terrains. Innovations such as quick-attachment systems and improved communication protocols between prime movers and implements are critical. Terrain adaptability and ergonomic design should be core considerations. While cultivators are in the diffusion phase, advanced weeding systems—particularly those employing laser and robotic technologies—remain in the research phase.

6.5. Seed drills and planters

While seed drills and planters are widely used for cereal crops, horticultural crop planting remains largely manual, particularly among smallholders. Transplanters for sugarcane bud chips and vegetables can significantly reduce weed incidence and enhance productivity. The sector shows a growing demand for integrated solutions encompassing bed preparation and precision seeding. Transplanters for sugarcane and vegetable crops, as well as multi-grain drills for smallholders, are currently in the prototype stage and require further development and demonstration.

6.6. Sprayers, spreaders, and dusters

Though chemical sprayers are commonly used, equipment for manure spreading and mulching is underdeveloped. Integration of fertilizer and water delivery with seeding operations is minimal. Most smallholders rely on manual or battery-operated knapsack sprayers, the majority of which are imported. Drone- and laser-assisted spraying trials have demonstrated promise, but widespread adoption is constrained by cost and technological limitations. Future emphasis should be placed on precision and environmentally safe application technologies, including electrostatic and guided systems. Less than 10% of agrochemicals effectively reach target plants, underscoring the urgent need for research into high-efficiency application methods. Institutional investment in this domain remains limited and should be expanded.

6.7. Post-harvest mechanization

While primary grain processing infrastructure is available, including equipment such as air screen cleaners, separators, sorters, and mills, post-harvest losses remain high, especially in smallholder and horticultural systems. There is a pressing need for near-farm processing facilities and affordable machinery for cleaning, grading, packing, and storage. Mechanized solutions for the handling and processing of horticultural produce are particularly underdeveloped. Equipment such as grain dryers, silos, seed treaters, vegetable washers and sorters, packaging units, and cold storage are essential to reduce spoilage and enhance value addition. Post-harvest mechanization is relatively advanced for major cereals but remains in the research and prototype stages for horticultural and small-farm contexts.

6.8. Sugarcane mechanization

In India, sugarcane cultivation relies heavily on manual labor, particularly planting and harvesting. Although mechanical land preparation is practiced, cane node cutting and bud chip transplanting are predominantly manual. Bud chip technology offers weed suppression and germination advantages and should be prioritized. Mechanization of key operations such as bud chip planting, root-zone irrigation, ratoon crop management, and harvesting should be accelerated. While bud chip transplanters are currently at the prototype stage, most other related technologies are in the extension phase. Given the crop's high labor and water demands, sugarcane mechanization warrants focused policy and research attention.

6.9. Fibre crop mechanization

Mechanization in cultivating fibre crops such as jute and cotton remains minimal. Manual labor predominates in tasks such as weeding and harvesting. Processing activities are predominantly conducted by large-scale industries. The jute processing sector urgently requires technological advancements. Most fibre crops are cultivated by small-scale farmers, necessitating the development of appropriate equipment and tools to facilitate mechanization tailored to their needs. For cotton, the introduction of locally manufactured processing equipment, such as compact ginning machines, is imperative. Jute mechanization demands the innovation of machinery for processes including retting, spinning, weaving, loom operation, quality control, and enhancement of efficiency and productivity. Currently, machinery for cotton harvesting and jute processing are in various stages of development or prototyping.

6.10. Horticultural machinery

Horticultural sectors encompassing vegetables, flowers, and fruits exhibit substantial export potential and contribute significantly to nutritional needs. However, the availability of mechanized equipment for vegetable cultivation is limited. Floriculture also remains under-mechanized. There is a notable absence of equipment for fruit harvesting, particularly from trees. Essential machinery includes harvesters for fruit trees, pruning tools, cleaning, grading, packaging equipment, and storage facilities. Presently, machinery for vegetable and fruit tree cultivation is in the prototype phase.

6.11. Livestock and poultry mechanization

Milk production, predominantly from small-scale farms, is conducted manually. There is a lack of electro-mechanical systems for animal feeding, cleaning, and monitoring. Waste generated in this sector, often utilized for biogas or vermicomposting, holds potential for conversion into other industrially valuable products. Poultry equipment for large-scale operations is primarily imported. There is a pressing need for sensor-based systems for feeding, watering, and disease detection in poultry farming. Automation is virtually non-existent in small-scale poultry operations. Small-scale equipment is essential for integrated farming systems that combine animal husbandry, poultry, and fisheries, which are significant revenue sources for small farms. Currently, only large animal farms employ milking machines. The development of smart machines capable of performing milking and cleaning operations is necessary. Implementation of Internet of Things (IoT)-based systems for data collection is crucial for early disease forecasting in livestock. Innovations in animal waste management for waste-to-energy (W2E) and waste-to-wealth (W2W) applications, automatic feeders, early disease warning systems, lameness detection platforms, image processing systems, and acoustic-based animal identification systems are required. Farm shelters designed to mitigate abiotic stresses using renewable energy or low-energy approaches should be developed. Presently, technologies for feeding, milking, manure management, health monitoring, animal handling, transport, and data management are in the research phase.

6.12. Fisheries mechanization

Various crafts and gear are utilized in fish culture and capture. In aquaculture, equipment such as feed dispensers, fish graders, and aerators is available; however, these require technical upgrades to enhance efficiency. There is a lack of commercial technology for live fish transportation. Machinery for fish drying and processing exists, yet indigenous solutions for fish cutting and meat-bone separation are absent, leading to reliance on imported machinery. Indigenous, energy-efficient solar dryers are gaining popularity for fish drying. Given the perishable nature of fish, refrigeration and cold storage facilities are vital for preservation. In India, traditional ammonia-based refrigeration systems are predominantly used. There is limited mechanization in culture fisheries. The application of mechanization is essential along India's coastal regions and within the fish and seafood processing industry. Both the West and East Coasts, including states like Andhra Pradesh, Tamil Nadu, Pondicherry, Kerala, West Bengal, and Odisha, require mechanization in capture and culture fisheries. Currently, crafts, gears, and post-harvest machinery in fisheries primarily operate on fossil fuels or electricity.

There is significant potential to convert these to renewable energy sources, particularly solar power. Refrigeration and cold storage units should be adapted to systems with lower Global Warming Potential (GWP). In alignment with the nation's carbon-neutral objectives, the development of boats, gears, and machinery with reduced GWP is essential to decrease the carbon footprint of fish and fishery products. Innovations such as automatic aerator systems, water temperature and quality monitoring and control systems, fish feed dispensers, and fish harvesting systems are needed. A live fish transportation system should be developed as a single unit or through waterless transportation methods to maximize benefits for fish farmers. Fisheries machinery development and indigenization are in the prototype and production stages.

6.13. Irrigation machinery

Predominantly, electrical pumps facilitate groundwater extraction, while tractor-mounted pumps are employed for surface water lifting. Although many of these pumps operate on fossil fuels, recent advancements have introduced solar-powered pumps as a sustainable alternative. Flood irrigation remains the predominant method for cereal crops, leading to significant water wastage; however, sprinkler systems are also utilized in certain regions. The adoption of drip irrigation is expanding, particularly for horticultural crops and select cash crops such as cotton and sugarcane. The future trajectory of irrigation systems is inclined towards sustainable, low-cost, and automated technologies. There is an imperative need for efficient subsurface irrigation systems tailored for high-density field crops, root zone watering mechanisms for horticultural systems, and the implementation of the Alternate Wetting and Drying (AWD) technique, which is currently promoted primarily for paddy cultivation. Advancements in the development of efficient irrigation equipment—including pumps, valves, dispensers, and monitoring systems—are essential. The integration of automatic control systems for water application is progressing through prototype and production stages.

6.14. Soil and water conservation machinery

The Broad Bed and Furrow (BBF) system has demonstrated efficacy in soybean cultivation on select farms and warrants broader implementation. Currently, there is a paucity of equipment designed for soil and water conservation and contour cultivation. While drip irrigation systems have gained acceptance among farmers for their water-saving capabilities, the adoption of irrigation schedulers and controllers remains limited. Precision farming continues to emerge as a significant area of development. Soil erosion and salinity pose substantial challenges; thus, there is a need for compact equipment for bunding, planting of bund crops such as bamboo and other trees, grading, installation of underground drainage systems, and maintenance of these infrastructures. Evapotranspiration-based irrigation scheduling systems and Artificial Intelligence/Internet of Things (AI/IoT)-supported sensor-based irrigation and farm management systems are poised to play a pivotal role in the future of Indian agriculture. Currently, soil and water conservation machinery is in the extension phase.

6.15. Conservation agriculture machinery

Conservation Agriculture (CA) represents a paradigm shift from unsustainable, intensive tillage-based agriculture to sustainable systems that enhance productivity and deliver ecosystem services. Globally, CA systems have been successfully adopted over 200 million hectares, with increasing acceptance. Available technologies include zero-till drills and Happy Seeders equipped with Super Straw Management Systems (Super SMS). Consequently, CA is now recognized as a cornerstone for agricultural sustainability, soil health, and productivity due to its positive impact on conserving natural resources and facilitating climate change adaptation and mitigation. Despite the development of no-till direct seeding equipment, widespread adoption remains limited.

Additionally, residue-in-situ machines are not commonly utilized. Many small-scale farms practicing 'Natural Farming' lack access to semi-automated tools and small machinery. There is a need for tools that support multi-cropping practices, encompassing field, horticultural, and forestry crops, as well as equipment for integrated farming systems involving animals, poultry, and fish. Currently, CA equipment is predominantly available for large-scale farms, with limited advancements for small-scale operations. The future holds promise for smallholders and hilly regions through the development and deployment of affordable and effective zero or minimum tillage implements for seeding, deep placement of fertilizers (both at seeding and post-seeding stages), and herbicide application. Single-pass CA planters compatible with two-wheel or small tractors should be made accessible to smallholders. Furthermore, there is a need for conservation agriculture equipment that facilitates need-based nutrient and chemical application. The development of multi-crop adaptable tools and equipment requires focused attention. Conservation tillage equipment, cover crop seeders, mulching equipment, soil testing instruments, compost spreaders, agroforestry tools, precision agriculture devices, and conservation drainage systems are currently at the extension and review stages.

6.16. Farm energy

Fossil fuels serve as the primary energy source for prime movers, while electricity is utilized for water pumping. With the exception of some solar-powered water pumps, renewable energy systems are scarcely implemented. Biogas production on small farms has not achieved sustainability. Energy consumers, such as machines and pumps, as well as the energy supply infrastructure, often exhibit low energy efficiency due to issues like unmaintained power factors. Emerging challenges, including sustainability, climate change, and net-zero obligations, are steering agricultural energy systems towards integration with energy conservation and alternative energy resources (Anon, 2022). Challenges persist across various levels, including maintaining quality standards and ensuring competitive pricing. The concept of a New Energy System for Agriculture (NESA) envisions a feasible mix of biofuels—comprising bio-hydrogen, bio-methane, biodiesel, bio-methanol, bioethanol, and other bio-derived hydrocarbons—sourced from surplus crop residues, judiciously utilized to balance soil organic load and demands for animal feed and similar competitive uses. This biofuel mix is anticipated to replace petro-diesel in a phased manner. Solar panels installed on farms can supplant fossil fuel usage for the country's power requirements. While solar panels contribute to reducing sunlight exposure, thereby potentially decreasing evapotranspiration, solar pumps should be efficient and controlled. Additionally, solar panels can facilitate the establishment of docking stations for charging farm prime movers, such as small tractors and robots. They can also meet energy needs in integrated farming systems involving animals and poultry. Solar equipment and biofuels are currently at production and extension stages.

6.17. Biotechnology machinery

The rapid advancement of biotechnology—encompassing genomics, proteomics, enzymology, and synthetic biology—necessitates highly specialized equipment, much of which remains either inaccessible or underdeveloped within the domestic context. This sector requires interdisciplinary technological integration involving blockchain, big data analytics, and artificial intelligence (AI) to support molecular characterization, data management, and predictive modelling tasks. Technologies such as cultured protein production, food printing, and lab-based fermentation systems are still in their nascent stages, with limited practical deployment. Future progress depends on the development of advanced instrumentation for genetic mapping, sequencing, genome editing (e.g., CRISPR-based systems), bioreactors for fermentation, and machinery for alternative protein extraction and processing. Currently, most biotechnology-related machinery remains at the research or prototype development stage, indicating significant opportunities for innovation and commercialization.

6.18. Controlled environment agriculture (CEA) equipment

Controlled Environment Agriculture (CEA), including greenhouses and net houses, offers promising avenues for enhancing productivity, resource use efficiency, and crop quality. While single and multi-span greenhouse structures are available for nurseries, floriculture, and off-season vegetable cultivation, they often lack region-specific customization in terms of climate adaptability, crop requirements, operational scale, and material localization (Pachiyappan, *et al*., 2022). Mechanization within CEA is minimal, with limited availability of tools for soil preparation, planting, pruning, weeding, spraying, and harvesting.

Net houses are increasingly adopted in floriculture and selective horticulture. However, high capital costs and limited availability of automation technologies constrain their scalability. It is imperative to develop naturally ventilated and semi-controlled structures suitable for smallholder and marginal farmers. Furthermore, automation in CEA remains challenging in high-temperature and high-humidity agroclimatic zones.

Technological gaps include precision management tools for transplanting, pruning, training, and harvesting; efficient systems for regulating temperature, humidity, light intensity, CO_2 concentration, irrigation, and nutrient delivery; and smart glazing materials capable of optimizing photosynthetically active radiation while supporting photovoltaic power generation. There is a growing need for sensor-driven environmental monitoring, drone-based surveillance and control systems, and biosensors for real-time detection of abiotic and biotic stress (Benke and Tomkins, 2017). Integration of AI and IoT for remote CEA management is advancing, with most innovations currently in production or extension phases.

6.19. Storage and logistics

Post-harvest losses in Indian agriculture remain significant due to inadequate storage and logistics infrastructure, particularly for cereal and horticultural crops. Current storage systems lack energy efficiency and are often unavailable to smallholder farmers. While cold storage facilities for fish and seafood exist, they are typically located far from landing centers and reservoirs, and are predominantly controlled by large institutional players, resulting in limited access and high spoilage rates.

There is an urgent need to develop decentralized, energy-efficient, and affordable storage solutions, including solar-powered cold storage facilities tailored to small and medium-sized farms. Semi-controlled storage systems could provide intermediate solutions where full-scale cold storage is economically infeasible. In fisheries, solar-based integrated heating and cooling systems could serve dual purposes—chilling and drying—thus enhancing value addition and reducing post-harvest losses in coastal regions.

Additionally, logistics systems require optimization based on the perishability and transport characteristics of farm produce. Research and development should prioritize the advancement of sustainable refrigeration, green cold chain logistics, and vending solutions for perishables such as fish and other aquatic products. These innovations are essential for enhancing food security, reducing losses, and improving farmer incomes.

6.20. Emerging technologies

A new generation of emerging technologies is reshaping the agricultural landscape, particularly unmanned land-based and aerial systems integrated with AI, machine learning, and big data analytics (De Clercq, *et al.*, 2018). These technologies offer considerable potential for precision farming, including real-time crop and climate monitoring, yield prediction, and targeted input application. However, their deployment in Indian agriculture is still at a nascent stage, with limited knowledge transfer and infrastructure support for widespread adoption.

There is a pressing need for structured technology transfer mechanisms, including farmer training, prototyping, modelling, and field validation of technologies prior to large-scale implementation. A cautious, context-specific approach is vital to ensure scalability and economic viability. As these innovations fall under the broader category of agricultural machinery, they should be developed in tandem with a sustainable and intelligent communication network for real-time advisories on crop selection, cultivation practices, and market linkages.

Importantly, all emerging technologies should adhere to principles of environmental sustainability. They should be energy-efficient, low in Global Warming Potential (GWP), and contribute minimally to greenhouse gas emissions such as CO_2 and NO_2. Future agricultural development should align with national goals of carbon neutrality, promoting the use of clean, green technologies that support climate-resilient farming systems.

7. Human Resource Development in Agricultural and Food Engineering

The agricultural and food engineering sector currently faces significant challenges in human resource development, primarily due to a mismatch between graduates' competencies and the industry's evolving demands. Agricultural engineers often lack proficiency in advanced machinery manufacturing processes, interdisciplinary integration, and emerging technologies such as automation, precision agriculture, and digital systems. The limited deployment of agricultural engineers in extension services further restricts knowledge dissemination and on-ground application.

A major gap persists in the interaction between academia, research institutions, industry, and farmers. Excessive vertical specialization in academic research has led to siloed knowledge generation, which is misaligned with contemporary agricultural systems' dynamic and cross-disciplinary requirements. It is imperative that student research agendas be aligned with real-world agricultural challenges to improve job readiness and promote problem-solving capabilities. Presently, students receive minimal practical exposure to on-farm operations and climate-resilient technologies.

To address these issues, curricula should integrate evolving technological domains such as information technology, communication systems, control engineering, and instrumentation. Faculty development through industry-academia exchange programs is essential to keep educators abreast of contemporary industrial practices. Agricultural universities should employ interdisciplinary faculty, including experts in electronics, mechanical, civil, electrical, and software engineering, as well as physics and environmental sciences, to enhance training outcomes.

Students and faculty should be mandated to make regular field visits, ideally one per semester, to understand ground realities and user-centric technology needs. Internships should be restructured to include on-farm stays, with project work oriented towards contemporary farming challenges. Furthermore, entrepreneurship among students should be actively promoted, particularly in areas such as agricultural robotics, precision agriculture, AI-based irrigation systems, IoT-enabled smart farming, carbon footprint monitoring, and certification mechanisms.

Collaboration with industry should focus on solving real-world problems, facilitating skill development, validating technologies, fostering innovative research, influencing policy, and enabling technology transfer. The agricultural engineering syllabus should be immediately restructured and thereafter reviewed periodically (every 3–5 years) to ensure continuous relevance.

Considering the expanding scope of mechanization, there is an urgent need to skill approximately 2.8 million individuals annually, projected to reach 3.6 million by 2030. Skill certification by accredited bodies should be a prerequisite for participation in government mechanization support schemes (ASCI, 2021). Preferential hiring practices should be instituted for certified professionals to enhance workforce quality and efficacy.

8. Reorienting Agricultural Mechanization Extension

Current agricultural mechanization policies, particularly those focused on input subsidies, are suboptimal. Existing regional disparities in subsidy schemes and an overwhelming focus on large-scale machinery, such as tractors, fail to address the mechanization needs of small and medium-scale farmers. There is a lack of targeted incentives for climate-smart technologies and low-emission agricultural practices.

Rather than offering capital subsidies for equipment ownership, a shift towards operational cost reimbursement (₹/hectare) via Direct Benefit Transfer (DBT) mechanisms is proposed. Under a “Lend-to-Rent” model, service providers would be compensated only after verified completion of services. This demand-driven approach encourages service efficiency and inclusivity, ensuring that smallholders also benefit.

Emphasis should also be placed on the deployment of AI, machine learning, and IoT systems for precision input management, climate adaptation, and real-time monitoring. Despite being the world’s largest producer of tractors, India exports only a fraction (approximately 10%). The country has the potential to emerge as a key exporter of agricultural machinery, particularly to developing regions in the Global South, provided domestic manufacturers are exposed to global market requirements.

To this end, academic curricula and research agendas should align with global agricultural mechanization trends. Government policy should support the development of export-oriented manufacturing capabilities and incentivize technological innovations.

9. Strategic Pointers for the Roadmap on Farm Mechanization

- ***Input optimization over output maximization***: To address food and environmental security challenges, future strategies should prioritize resource-use efficiency over mere productivity gains.
- ***Diversification beyond cereals***: Given the near-saturation of tractor adoption (1 tractor per 10 hectares), attention should shift towards implements and machinery for non-cereal crops (e.g., cotton, sugarcane, fruits, vegetables), as well as fisheries and livestock systems.
- ***Sustainable tillage and conservation agriculture***: There should be reduced focus on intensive tillage and greater support for conservation agriculture, precision farming, and natural resource management tools.
- ***Post-harvest infrastructure***: Investments in logistics, cold chains, and green storage technologies should be scaled to reduce perishability losses, especially in horticulture.
- ***Subsidy reforms***: Equipment purchase subsidies should be redirected toward farm operation subsidies. Given that a large proportion of farmers rent rather than own machinery, this would enhance equitable access and utilization of mechanization assets.
- ***Curriculum modernization***: Agricultural education should undergo dynamic revisions to incorporate inter- and transdisciplinary approaches, ensuring relevance to real-world challenges and technological advancements.
- ***Demand-driven research and farmer-centric innovations***: Research institutions should respond to on-the-ground challenges such as inefficient chemical spraying, overuse of water, inadequate storage, and labor shortages. Knowledge dissemination should be prioritized over academic publication.

10. Epilogue

Agricultural mechanization is a critical engineering intervention required for transitioning Indian agriculture towards a model that is sustainable, efficient, and a dignified source of livelihood. Agricultural engineering encompasses a multidisciplinary approach, drawing from mechanical, civil, electrical, electronics, environmental, and software engineering, along with food science and economics. Its applications span mechanization, power and energy management, irrigation systems, soil and water conservation, post-harvest infrastructure, and value-added technologies.

Recent advancements such as controlled environment agriculture (CEA), biosensors, digital monitoring systems, unmanned aerial and ground vehicles, and AI-enabled autonomous machinery offer transformative potential. These technologies aim to alleviate the physical burden of farming and attract a new generation of skilled professionals into the agricultural sector.

Agricultural engineering, which played a limited role during the Green Revolution, should now become central to India's agricultural transformation. The current decade presents a historic opportunity to leverage engineering innovations to enhance agriculture's productivity, profitability, and sustainability. The collective efforts of academia, industry, extension agencies, and policymakers will be critical in realizing this vision and in positioning India as a global leader in sustainable agri-engineering by 2047.

This strategic document reflects a preliminary consensus among key stakeholders and should be further detailed for implementation. It is imperative that engineering inputs be mainstreamed, not as ancillary technologies, but as integral elements of an inclusive, modern agricultural system.

11. References

Anonymous. (2015). Transforming agriculture through mechanization: A knowledge paper on Indian farm equipment sector. FICCI.

Agriculture Skill Council of India. (2022). Skill gap analysis of Indian farm mechanization sector. ASCI.

Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. Sustainability: Science, Practice and Policy, 13(1), 13–26. https://doi.org/10.1080/15487733.2017.1394054

Bhattarai, M., Singh, G., Takeshima, H., & Shekhawat, R. S. (2020). Farm machinery use and the agricultural machinery industries in India:

Status, evolution, implementations, and lessons learned. In X. Diao, H. Takeshima, & X. Zhang (Eds.), An evolving paradigm of agricultural mechanization development: How much can Africa learn from Asia? (pp. xx–xx). International Food Policy Research Institute.

De Clercq, M., Vats, A., & Biel, A. (2018). Agriculture 4.0: The future of farming technology. World Government Summit. https://www.oliverwyman.com/our-expertise/insights/2018/feb/agriculture-4-0--the-future-of-farming-technology.html

Food and Agriculture Organization & Zhejiang University. (2021). Digital agriculture report: Rural e-commerce development experience from China. FAO. https://doi.org/10.4060/cb4960en

Future Market Insights. (2022). By 2032, the value of agricultural equipment market is expected to reach US$ 108.86 Bn. https://www.prnewswire.com/news-releases/by-2032--the-value-of-agricultural-equipment-market-is-expected-to-reach-us-108-86-bn--future-market-insights-inc-301629480.html

Government of India. (2022). Farm mechanization: A catalyst for sustainable agricultural growth. Indian Economic Survey 2022. https://www.indiabudget.gov.in/economicsurvey/

Investment Information and Credit Rating Agency. (2024). Indian tractor industry report 2024. ICRA.

Mehta, C. R., Bargale, R. A., Chandel, N. S., & Kumar, M. (2023). Farm mechanization in India: Status and way forward. Agricultural Mechanization in Asia, Africa and Latin America (AMA), 54(2), 75–88.

Mehta, C. R., Chandel, N. S., Jena, P. C., & Jha, A. (2019). Indian agriculture counting on farm mechanization. Agricultural Mechanization in Asia, Africa and Latin America (AMA), 50(1), 84–89.

Ministry of Agriculture & Farmers Welfare. (2018). Report on monitoring, evaluation and impact assessment of SMAM. Government of India. https://farmech.dac.gov.in/SMAM/Evaluation%20Report%20SMAM/Final%20Report%20M&E%20SMAM%20.pdf

National Academy of Agricultural Sciences. (2019). Vertical farming (Policy Paper No. 89). NAAS.

NITI Aayog. (2018). Demand and supply projections towards 2033: Crops, livestock, fisheries and agricultural inputs. Working Group Report.

Pachiyappan, P., Kumar, P., Reddy, K. V., Kumar, K. N. R., Konduru, S., Paramesh, V., Rajanna, G. A., Shankarappa, S. K., Jaganathan, D., Immanuel, S., *et al*. (2022). Protected cultivation of horticultural crops as a livelihood opportunity in western India: An economic assessment. Sustainability, 14(12), 7430. https://doi.org/10.3390/su14127430

Rao, A. (2024, February 20). Farm mechanization in India's agriculture sector: Challenges and opportunities. India Briefing. https://www.india-briefing.com/news/india-farm-mechanization-sector-opportunities-challenges

Standing Committee on Agriculture, Animal Husbandry and Food Processing. (2023). Research and development in farm mechanization for small and marginal farmers in the country (2022–23). Sansad. https://sansad.in/getFile/lsscommittee/Agriculture,%20Animal%20Husbandry%20and%20Food%20Processing/17_Agriculture_Animal_Husbandry_and_Food_Processing_58.pdf?source=loksabhadocs

Singh, Gajendra and William Chancellor. 1974. Studies of Relations between Farm Mechanization and Crop Yield. AMA (Agricultural Mechanization in Asia) 5(10): 1821, 85.

Singh, G., & Chancellor, W. (1975). Energy inputs and agricultural production under various regimes of mechanization in Northern India. Transactions of the ASAE, 18(2), 252–259.

Singh, G., & Doharey, R. S. (1999). Tractor industry in India. Agricultural Mechanization in Asia, Africa and Latin America (AMA), 30(2), 9–14.

Singh, G. (2000). Agricultural engineering education in India. Agricultural Engineering: The CIGR Journal of Scientific Research and Development, II.

Singh, G. (2001). Relationship between mechanization and agricultural productivity in various parts of India. Agricultural Mechanization in Asia, Africa and Latin America (AMA), 32(2), 68–76.

Singh, G. (2013). Agricultural mechanization in India. In J. Kienzle, J. E. Ashburner, & B. G. Sims (Eds.), Mechanization for rural development: A review of patterns and progress from around the world (Integrated Crop Management Vol. 20-2013). FAO.

Singh, G. (2015a). Agricultural mechanization development in India. Indian Journal of Agricultural Economics, 70(1), 64–82.

Singh, G. (2015b). Agricultural mechanization situation in Asia-Pacific region. In Agricultural mechanization and testing of agricultural machinery in Asia-Pacific region. Center for Sustainable Agricultural Mechanization, United Nations – ESCAP.

Singh, G. (2015c). Agricultural mechanization in India. In Farm machinery to feed the world. Club of Bologna, Milano, Italy.

Trendov, N. M., Varas, S., & Zeng, M. (2019). Digital technologies in agriculture and rural areas (Briefing Paper). Information Technology Division, Food and Agriculture Organization of the United Nations. https://www.fao.org/3/ca4887en/ca4887en.pdf

World Bank. (2022). Data on production and yield in different countries. The World Bank. https://data.worldbank.org/indicator

Yukiko, N. (2024). Farm mechanization in India advancing with custom hiring – transition from agroindustry to agroecology. Monthly Report, February 2024. Mitsui & Co. Global Strategic Studies Institute.

8 Climate Action

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1. Context

Climate change is one of the most urgent challenges confronting our planet today, denoting the prolonged alterations in global or regional climate patterns, chiefly propelled by human actions that discharge greenhouse gases into the atmosphere, trapping heat and driving up the Earth's average temperature. The primary cause behind climate change stems from human activities, notably the combustion of fossil fuels, deforestation, and industrial operations. Coal, oil, and natural gas combustion for electricity generation, transportation, and industrial processes emits substantial quantities of carbon dioxide (CO_2), constituting the foremost greenhouse gas (GHGs), and accounts for approximately 65% of global greenhouse gas emissions. Deforestation and land-use alterations are equally significant, whereby the clearance of forests for agriculture, urban expansion, and other human endeavors liberate stored carbon into the air, contributing to roughly 11% of global greenhouse gas emissions. Agricultural and land use changes, including rice cultivation, livestock rearing, and fertilizer application, emit methane and nitrous oxide, potent greenhouse gases, accounting for around 24% of global emissions in 2020 (FAO, 2020).

Climate change manifests in various ways, yielding significant impacts across the globe. Rising temperatures, spurred by a 1.1°C (2°F) increase since the late 19th century, intensify heat waves, posing risks of heat-related illnesses and straining water resources and agriculture. Alterations in precipitation patterns result in heightened droughts and heavy precipitation, disrupting water supplies, agriculture and ecosystems, fostering food insecurity and displacement (Pathak *et al.*, 2021). The

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accelerated melting of glaciers and ice sheets, particularly in polar and mountainous regions, contributes to rising sea levels, causing coastal erosion, flooding, and the displacement of communities. The oceans absorb excess heat, leading to warming, expansion, and acidification, which harm marine life and ecosystems. Climate-induced shifts affect plant and animal species, potentially driving declines in biodiversity and even extinction (Srinivasa Rao *et al*., 2016). Additionally, climate change facilitates the spread of diseases and exacerbates extreme weather events, posing health risks and straining healthcare systems. Economic and social impacts abound as agriculture, infrastructure, and communities bear the brunt of climate-related disruptions, leading to significant losses and displacement (IPCC, 2021). Furthermore, ecological ramifications are evident in the degradation of coral reefs and the broader loss of biodiversity, underscoring the urgent need for concerted global action to mitigate climate change's far-reaching consequences.

Economic losses due to climate change in agriculture and food production arise from damages inflicted by droughts, floods, and extreme weather events, disrupting farmers' crop yields and income streams (Burke *et.al*. 2015). Property and infrastructure suffer as sea-level rise, coastal erosion imperil coastal assets, and extreme weather events wreak havoc on buildings and transportation networks. Disruptions to supply chains and trade ensue from weather-related delays and alterations in raw material availability and pricing. Health costs mount as climate change exacerbates illnesses and injuries, while increased energy and water costs burden households and businesses. Ecosystem degradation further amplifies economic losses, affecting industries reliant on ecosystem services (Compston, 2018). Notably, these losses reverberate through job markets, income levels, and overall economic growth, with developing countries and vulnerable communities bearing disproportionate burdens due to limited resources. Recognizing the long-term economic impacts underscores the imperative for proactive measures to mitigate emissions and adapt to climate change, safeguarding economies and societies against the adverse effects of a warming planet.

2. Mitigation Targets and Commitments by the Government of India

2.1. Paris agreement

India is one of the pro-active countries in the United Nations Framework Convention on Climate Change (UNFCCC) in terms of global climate change negotiations and implementing different climate actions at the ground level (Srinivasa Rao *et al*.,2019). The Paris Agreement (PA, 2015), COP 21, serves to restrict global warming to well below 2°C (3.6°F) above pre-industrial levels and strive to limit it to 1.5°C (2.7°F). India is a signatory to the Paris Agreement to achieve the targets. The agreement incorporates several key elements:

2.1.1. Nationally determined contributions (NDCs)

Each nation designs its own emissions reduction plan, known as an NDC. These plans are revisited and strengthened periodically, fostering a system of continuous improvement over time (NDC, 2021).

2.1.2. Transparency and reporting

Countries are obligated to report on their emissions reductions, progress made towards their NDCs, the climate impacts they experience, and the measures they're taking to adapt. This transparency fosters accountability and allows for collective progress tracking.

2.1.3. Climate finance

Developed nations are expected to financially support developing countries. This assistance is crucial for developing countries to implement mitigation and adaptation efforts, ensuring a more equitable global approach (UNFCCC).

2.1.4. Global stock take

Beginning in 2023, a mechanism will assess the collective progress of all countries towards the long-term goals of the Agreement every five years. This 'stock take' allows for course correction and ensures all nations are moving in the right direction.

2.1.5. Enhancing adaptation

Recognizing the inevitable impacts of climate change, the Agreement highlights the importance of adaptation measures. It aims to strengthen countries' ability to adapt to the challenges they already face and will continue to face in the future.

2.2. Net zero emission commitment

The commitment to achieving net-zero entails balancing greenhouse gas emissions produced with those removed from the atmosphere. This requires offsetting any remaining emissions through activities like reforestation or carbon capture and storage technologies. Greenhouse gas emissions from fossil fuels are projected to reach a record 36.8 billion metric tons in 2023, an increase of 1.1% over 2022, according to an annual report by the Global Carbon Project. India's Third National Communication to the United Nations Framework Convention on Climate Change was submitted on December 9, 2023. It reveals that the energy sector contributed the most to the overall anthropogenic emissions (75.81%), followed by the agriculture sector (13.44%), Industrial Process and Product Use (IPPU, 8.41%), and Waste (2.34%).

In 2022, India updated its NDC, according to which the target to reduce emissions intensity of its GDP has been enhanced to 45% by 2030 from the 2005 level, and the target on cumulative electric power installed capacity from non-fossil fuel-based energy resources has been enhanced to 50% by 2030 (Table 1). India has been spending significant resources on adaptation-relevant actions, despite the competing demands for limited resources in a developing economy (https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1989495).

Key components of the net-zero commitment encompass emission reduction, carbon removal and climate resilience. The Paris Agreement provides the framework, and net-zero commitments translate its goals into achievable targets. India's achievements against the NDC targets are presented in the table 1 (https://moef.gov.in/wp-content/uploads/2024/03/Annual-Report-English-2023-24.pdf):

Table 1. India's Achievements against the NDC targets and revised targets by the year 2030.

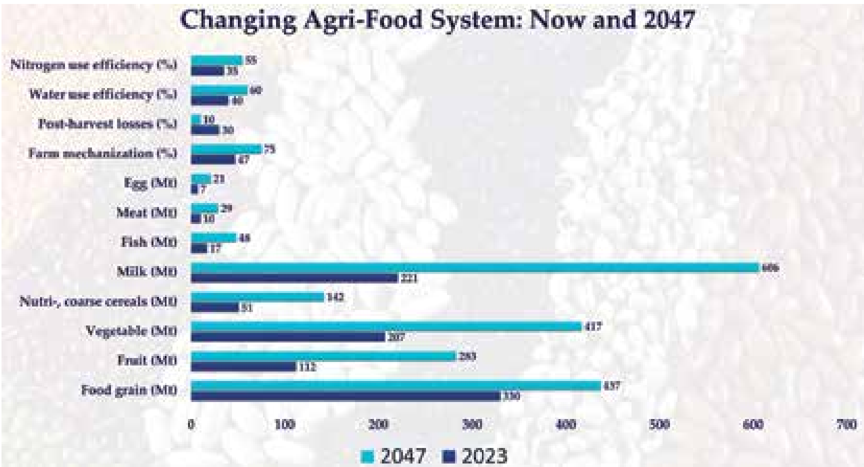
NDC (2015)	Target (2030)	Achievement	Revised targets
Reduction Emissions Intensity GDP	33-35% over 2005 level	33% (2019)	45%
Non-Fossil Electric Installed Capacity	40% cumulative	43.8% (2023)	50%
Additional Carbon Sink	2.5-3.0 billion tons	1.97 billion tons (2021)	2.5-3.0 billion tons

3. Opportunities for Net Zero of GHGs in the Agriculture Sector

Agriculture contributes 13.44% of GHGs in India. Though the country is on track towards meeting the Paris Agreement (PA) commitments and achieving Net Zero Carbon (NZC) emissions by 2070, it would not be possible unless all other sectors, like agriculture, contribute to the mission of NZC. Currently, the agriculture sector's major emphasis is on adaptation to climate change and its impacts; mitigation co-benefits of adaptation are equally important in achieving NZC (Figure 1).

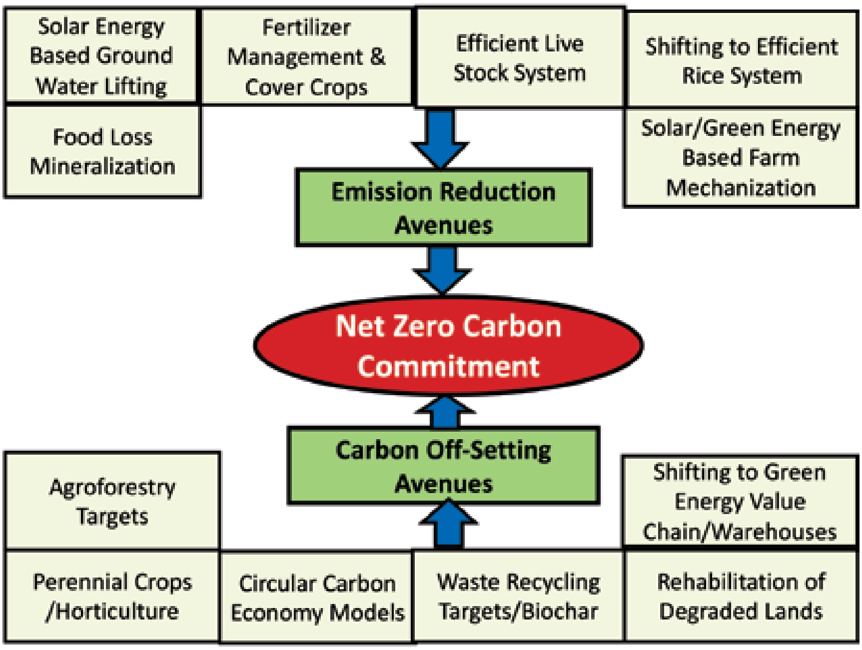
The agriculture sector is critical for the Indian economy and the livelihoods of a large population; it contributes to food and nutritional security, health, and agri-exports. The country's food needs, and crucial technological impact targets include improved N use efficiency, water use efficiency, farm mechanization and food loss reduction targets (H. Pathak, Personal Communication) (Figure 1). This underlines that a strong, technically managed farming can have a larger mitigation potential if these technologies are implemented synergistically. Various agriculture sub-sectors like field crops, horticulture, livestock, fishery and poultry can be potential avenues if managed with technically sound precision farming practices. Livestock-dairy is the largest contributor, and systems like rice-paddy, fertilizer and manure application, soil tillage mediated carbon loss into the atmosphere, besides improper management of farm and agri-industry waste, coal-based energy for lifting irrigation water, etc., are other sub-sectors which emit a considerable amount of GHGs. Indirectly, agro-industries related to fertilizer and pesticide manufacturing companies, their transportation, farm machinery used energy, transportation of agri inputs and outputs in terms of agri-value chains and cold storage infrastructure also contribute. Still, these emissions are accounted for in the industry and transport sectors.

Figure 1. *Food needs and associated technology efficiency targets by Amrit kaal (2047).*



Two kinds of strategies contribute to the mitigation potential of agriculture and allied sectors in India. These are: (a) Emission reduction avenues, and (b) Fixing of atmospheric CO_2 into the agricultural systems (Figure 2).

Figure 2. *Carbon emissions and offsetting strategies in the agriculture sector.*



3.1. Mitigation through input management

Fertilizers, water management, and agri-inputs are pivotal components in realizing net-zero emissions within the agricultural sector. Fertilizers, notably nitrogen-based variants, pose a substantial emissions challenge due to the utilization process, primarily emitting nitrous oxide, a potent greenhouse gas. To mitigate these emissions, strategies such as precision agriculture, slow-release fertilizers, optimizing nutrient application and organic alternatives offer promising solutions, and enhance soil health. Water management practices can contribute to emissions, particularly through traditional flood irrigation methods (Mrunalini *et al*., 2022; Srinivasa Rao *et al*., 2021). Implementing water conservation techniques like drip irrigation and rainwater harvesting not only enhances water efficiency but also reduces associated energy requirements and emissions. Concurrently, embracing climate-smart agriculture practices, which integrate water conservation alongside other sustainable methodologies, bolsters system resilience in the face of climate change (Bhattacharyya 2022). Additionally, agri-inputs encompassing pesticides, herbicides, and fungicides necessitate sustainable alternatives and integrated pest management strategies to minimize environmental impact. Transitioning towards a net-zero agricultural paradigm demands a holistic approach encompassing optimized fertilizer usage, water conservation, adoption of sustainable agri-inputs, and broader regenerative practices enhancing soil health and carbon sequestration (Jat *et al*., 2016). Advancements in precision agriculture and deployment of data-driven technologies and renewable energy sources further contribute to emission reductions, underscoring the significance of innovation and technology. Moreover, governmental policies advocating for sustainable practices, supporting research in eco-friendly alternatives, and providing incentives for their adoption are imperative for effecting widespread change (Siraj *et al*., 2022). By confronting these challenges and harnessing the potential of sustainable methodologies, agriculture can forge a path towards a net-zero future, ensuring food security while mitigating climate change.

Sustainable crop management practices reduce emissions and enhance soil carbon sequestration, including minimal tillage, crop rotation, and cover cropping. Precision agriculture techniques like variable rate fertilizer application and site-specific crop management optimize input utilization, thus reducing emissions associated with inefficient application. Efficient nutrient management strategies, such as utilizing organic fertilizers and implementing practices like fertigation and slow-release fertilizers, minimize reliance on synthetic nitrogen fertilizers, major sources of nitrous oxide emissions. Water management plays a crucial role in emissions mitigation, with efficient irrigation techniques like drip irrigation and deficit irrigation reducing water application need and associated energy consumption and emissions. Integrated pest management (IPM) strategies and promoting bio-pesticides aid in reducing emissions linked to synthetic pesticide production and application. Developing and adopting climate-smart crop varieties further enhances resilience and diminishes emissions associated with crop management practices. Achieving net-zero emissions necessitates a holistic approach combining these strategies and practices, underlining the importance of collaboration among stakeholders to promote sustainable and climate-friendly crop management practices at all levels of the agricultural sector (Samra and Srinivasa Rao, 2021).

Plant nutrient application as per Soil Health Cards (SHC) reduces the environmental load of chemicals. A reduction in the use of fertilizers will reduce soil and water pollution. With the use of SHC, there is less application of fertilizers that reduce GHG emissions and help mitigate climate change. Approximately 1.1 Mt CO_2 eq. GHG emissions have been mitigated annually by the technology. Application of fertilizer and micronutrients based on SHC recommendations resulted in 8-10% savings in fertilizer use. The country has saved about 0.8 Mt of nutrients per year. The LCC-based N application enhanced rice yield by 9-13% over conventionally applied urea (Nayak *et al*., 2017). Reduce nitrate leaching by 18-40%. Use of LCC reduces N_2O emissions by 13-21%. Approximately 0.1 Mt CO2 eq per year, GHG emissions have been mitigated by the technology (Bijay-Singh *et al*., 2020). Increase N recovery efficiency by 9-12% and potentially save 18-27% urea (Sharma *et al*., 2022). This technology saves about 0.1 Mt of N at Rs. 77 crores per year.

Adoption of zero tillage and other RCTs has expanded to cover about 2.5 million ha and has a greater potential for expansion in both irrigated and rainfed conditions (Pathak *et al*. 2021; Prasad *et al*., 2016; Jain *et al*., 2014). The farmers of the northwestern region are increasingly adopting raised-bed planting and laser land levelling. Reduction in water use by 10% and cost of production by 15% (Rs 2,000 to 3,000 per ha) and increase in net return by 27% (Pathak *et al*., 2021). It reduced diesel consumption by 15%. Thus, 37.5 ML of diesel worth Rs. 337 crores at the current price of Rs 87.62/litre have been saved annually. Resource conservation technologies increase resource efficiencies and reduce GHG emissions (12-33%). The technology has mitigated approximately 0.3 Mt CO2 eq per year GHG emissions. Legume-based systems can also significantly build up soil carbon and N fertility.

Bio fertilizers help to increase the soil by providing nutrients and a natural environment in the rhizosphere. Applying biofertilizers results in less use of fertilizers, reducing GHG emissions. Blue-green algal systems and Azolla could minimize methane emission from flooded rice soils in paddy-paddy rotation. As a dual crop, these biofertilizers minimize the global warming potential from flooded paddy. Approximately 0.2 Mt CO_2 eq per year, GHG emissions have been mitigated by the technology. Biofertilizers can supplement costly chemical fertilizers (N, P) by 10-20% when used along with the chemical fertilizers (Kumar *et al*., 2022).

Neem oil Coated Urea (NCU) application increased the yield of sugarcane and cotton by 8.7 and 4.3%, respectively (Singh *et al*., 2016). It was reported at 38% in soybean, 34% in pigeonpea and 9% in paddy (Ramappa and Manjunatha, 2019). A higher NUE of 58.71% in transplanted rice was noticed under NCU compared to Sulphur coated urea (SCU) and normal urea (Kumar *et al*., 2015). NCU reduced the global warming potential by

4-5% as compared to urea alone. The application of NCU reduced the N_2O emissions by 10 % from the transplanted rice field and 63% in the wheat field (Mazumdar *et al*., 2000). The NCU weight per bag is already reduced by 10% in India (by reducing a 50 kg bag to 45 kg), directly saving input up to 10%. About 3 million tons (Mt) of urea, valued at 10% of the urea subsidy, can be saved. Further, in SCU, the nitrogen content has been reduced to 37% and the weight per bag to 40 Kg, which will economize the cost of nitrogenous fertilizer by enhanced nitrogen use efficiency (NUE).

Lifting water consumes a major share of energy in the agriculture sector. Effective rainwater harvesting in terms of farms potentially reduces energy consumption and contributes to carbon emission reduction. Micro irrigation and fertigation save both fertilizer and water, thus contributing to nutrient as well as water use efficiency in the agricultural systems. There is about a 25% saving in fertilizers due to fertigation, apart from improved crop performance (Jain, 2021). Automation in drip irrigation is one advancement of research in this field. ICAR-IIWM has developed irrigation schedules for automated drip irrigation in the banana crop. Based on the water-saving figures, it is estimated that approximately 15.2 billion cubic meters of water are being saved by drip irrigation per year and 4.3 billion cubic meters by sprinkler irrigation per year (Narayanamoorthy, 2006).

3.2. Mitigation through agri-horticulture systems

Managing agricultural and horticultural crops holds pivotal significance in realizing net-zero emission commitments. Perennial cropping systems enhance carbon sequestration and diversify income streams, while renewable energy integration displaces fossil fuel usage and diminishes energy-related emissions. Exploring carbon capture and storage technologies helps offset remaining emissions from agricultural activities. Perennial trees contribute to the long-term carbon storage besides providing food and nutrition benefits in the form of a win-win situation of food and environmental security. About 10 million hectares of land area under perennial fruit crops in India also provides a wider opportunity in the form of land degradation neutrality, carbon storage, N-fixing legume as intercropping and conservation agriculture practices, particularly in wide-spaced horticulture systems.

3.3. Mitigation through the livestock sector

Livestock production, particularly methane emissions from enteric fermentation in ruminant animals like cattle, sheep, and goats, contributes significantly to GHG emissions. Addressing these emissions is crucial for achieving net-zero emissions in agriculture. Key strategies include improved feed management, such as optimizing diets with high-quality forages and exploring feed additives or supplementation strategies to reduce methane production. Breeding programs that select animals with lower methane emissions, alongside ensuring optimal animal health and welfare, play pivotal roles. Effective manure management techniques like anaerobic digestion and composting can capture methane for energy generation while reducing emissions. Implementing rotational grazing and selecting improved forage species can optimize pasture utilization and enhance soil health, contributing to carbon sequestration. Emerging technologies like methane-inhibiting vaccines and precision livestock farming offer promising avenues for future mitigation. Conducting life cycle assessments and advocating for supportive policies and incentives are crucial considerations. Challenges such as economic viability and consumer preferences must be addressed through financial support, incentives, and gradual shifts in consumer behavior. We can propel the livestock sector towards sustainability and a lower-carbon future by integrating these strategies and fostering research, innovation, and collaboration.

3.4. Mitigation through agroforestry

Afforestation, land use change, and agroforestry practices are pivotal components in pursuing net-zero emission commitments, offering multifaceted contributions towards carbon sequestration, ecosystem restoration, and sustainable land management. Through afforestation initiatives, the establishment of new forests on previously deforested or degraded lands presents a potent avenue for carbon dioxide absorption via photosynthesis and biomass accumulation, while concurrently yielding co-benefits like biodiversity conservation and water cycle regulation. Similarly, the strategic conversion of degraded or marginal lands into productive ecosystems, coupled with the restoration and conservation of natural habitats such as peat lands and mangroves, bolsters carbon storage and safeguards vital carbon sinks. In tandem, agroforestry systems emerge as dynamic solutions, integrating trees, shrubs, and agricultural activities to foster diversified and sustainable production landscapes. By sequestering carbon in biomass and soils, while simultaneously furnishing essential resources like food, fodder, and fuel, agroforestry exemplifies the fusion of ecological and economic benefits. Sustainable forest management further underpins these efforts, emphasizing practices like selective logging and old-growth forest preservation to uphold and enhance carbon sequestration potential. Integral to the efficacy of these endeavors are robust carbon accounting and monitoring mechanisms, bolstered by remote sensing technologies and ground-based measurements, to inform policy decisions and track progress towards net-zero emissions targets. Moreover, the enactment of supportive policies and financial incentives, such as REDD+ and carbon markets, serves to galvanize afforestation, land use change, and agroforestry endeavors. By integrating these strategies into climate mitigation frameworks, the collective pursuit of net-zero emissions is not only facilitated but also enriched by ancillary benefits encompassing biodiversity conservation, soil health enhancement, and heightened resilience to climate vagaries. Nonetheless, mindful implementation that prioritizes sustainability and equity, while respecting local communities' rights and livelihoods, is paramount to ensure the enduring efficacy of these interventions.

The estimated area under agroforestry in India is 25.31 million hectares (M ha) or 8.2% of the country's total geographical area. According to the Forest Survey of India (FSI), India's present forest and tree cover is 79.42 M ha, which is 24.39% of the overall geographical area. There are several location-specific agroforestry models available. These location-specific agro-forestry systems have greater potential in implementing the Green India Mission of the Government of India. Internal rate of return (IRR) from 25 to 68 and benefit cost ratio of 1.01 to 4.17 for 24 AFS from various agro-climatic areas of the country. Agro-forestry systems fix carbon up to 10 $t^{-1} ha^{-1} yr^{-1}$ with an average sequestration capacity of 25 t ha^{-1}. At the country level, current agroforestry systems are estimated to mitigate 109.34 Mt of CO_2 annually, which may counteract 1/3rd (33%) of the total GHGs released from the agriculture sector (Dhyani *et al.*, 2009). India intends to reduce the emissions intensity of its GDP by 33 to 35% by 2030 from the 2005 level and to create an additional C sink of 2.5 to 3 billion tons of CO_2 equivalent through additional forest and tree cover by 2030 (Rizvi, 2021). Agroforestry will be crucial in meeting India's Intended Nationally Determined Contribution (INDC) targets, as there is no further scope to put more areas under forest land (Govt. of India Commitments, Paris Agreement).

3.5. Mitigation through food value chain development

Reducing inefficiencies and strengthening food value chains can contribute to achieving net-zero emission commitments. Moving along the value chain, optimizing energy efficiency and waste management in food processing facilities mitigates emissions, and investing in sustainable transportation and storage infrastructure minimizes carbon footprints during distribution. Finally, household practices, including sustainable consumption patterns and energy-efficient cooking methods, significantly reduce emissions.

3.6. Mitigation through agri-energy management and warehouses

Transitioning to renewable sources like solar and wind power is important in achieving the net-zero emission commitment in the energy sector. Developing smart grid infrastructure facilitates the efficient distribution and integration of renewable energy sources. Similarly, in warehousing, energy-efficient design features such as LED lighting and improved insulation significantly curtail energy consumption, while integrating renewable energy sources like rooftop solar panels reduces reliance on fossil fuels. Optimizing refrigeration systems in cold storage facilities minimizes energy use while preserving food quality. Collaboratively, sectors can harness waste-to-energy solutions to utilize methane emissions from agricultural waste for energy production, while precision agriculture and data management enhance resource efficiency and supply chain optimization, reducing energy consumption and emissions. Government incentives, research, development efforts, and embracing circular economy principles are integral components for fostering sustainable practices and achieving long-term emissions reductions across all sectors.

3.7. Food Systems and Green Foods

The imperative role of food systems, green foods, and health in achieving net-zero carbon emission commitments underscores the necessity of transitioning to a sustainable and eco-conscious food production paradigm. Food systems significantly contribute to global greenhouse gas emissions, with agriculture and land-use changes comprising approximately 65% of food-related emissions. The implementation of sustainable practices across various facets of food production, processing, and distribution is indispensable for mitigating emissions and realising net-zero objectives. Concurrently, promoting the consumption of green foods, characterized by their environmental sustainability and nutritional value, holds promise in curbing 29–70% of food-related greenhouse gas emissions while concurrently enhancing human health. By concentrating efforts on fostering sustainable food systems, advocating for the adoption of green foods, and prioritizing health outcomes, the food industry can significantly contribute to achieving net-zero carbon emissions.

3.8. Waste to wealth- circular carbon economy

The notion of a "waste to wealth" circular carbon economy emerges as a pivotal mechanism in fulfilling net-zero carbon emission commitments, ushering in a sustainable and low-carbon trajectory for the future. Central to this paradigm is the promotion of resource efficiency, waste reduction, and harnessing carbon emissions. Through the reduction of waste generation via strategies such as product redesign and industrial symbiosis, energy and emissions linked to resource extraction, processing, and disposal can be minimized. Additionally, using waste-to-energy technologies like incineration and anaerobic digestion presents an opportunity to extract energy from waste streams, displacing fossil fuel usage and mitigating emissions. Simultaneously, converting waste materials into valuable products, such as biofuels and construction materials, not only generates new revenue streams but also reduces emissions associated with conventional production processes. Moreover, adopting carbon capture technologies in industrial processes prevents carbon dioxide from being released into the atmosphere, with captured carbon utilized for various applications or stored underground through carbon sequestration methods (Srinivasarao *et al*., 2013; 2014). Embracing a bio economy framework further advances sustainability by promoting the use of renewable biological resources for bio-based products, thereby curbing reliance on fossil-based resources and reducing emissions.

Utilization of residues of both irrigated and rainfed crops available to recycle (to the extent of 300 mt per year) in terms of in-situ management through suitable farm machinery contributes to improving soil organic carbon buildup and reducing the N requirements of subsequent crops. Major alternate usage of paddy straw as an economic resource are: (i) Biomass Power Projects, (ii) Co-firing in Thermal Power plants, (iii) Feedstock for 2G Ethanol plants, (iv) Feedstock in Compressed Biogas plants, (v) Fuel in Industrial Boilers, WTE plants, Brick Kilns etc., and (vi) Packaging materials, Agri-panels etc. (Annual Report, MoEF & CC 2023-24). The effect of various in-situ and ex-situ technology options reduced paddy residue burning events in several states (Table 2). Such technology impacts the overall mission of the waste-to-wealth program and has a greater potential for the mitigation of GHGs during the *Amrit Kaal*.

Table 2. Paddy residue burning event reduction (15th September- 30th November).

Punjab		Haryana		UP (NCR)		Total (including Delhi and NCR districts of Rajasthan)	
2021	2022	2021	2022	2021	2022	2021	2022
71,304	49,922 (-30%)	6987	3661 (-48%)	252	198 (-21%)	78550	53792 (-32%)

Another important avenue is converting crop residues into valuable biochar. Many innovative farmers are converting crop residue into biochar, which can potentially offset India's GHG emissions. Biochar could sequestrate an average of 376.11 Mt of carbon dioxide equivalent carbon in the soil and help India reduce 41.41–63.26% of emissions from agricultural and its allied activities.

3.9. Replication of carbon-positive villages

ICAR's flagship program "National Initiatives on Climate Resilient Agriculture (NICRA) contributed to the establishment of 151 model climate resilient villages (CRV) in 151 climate vulnerable districts of India with a technology package of soil-water-crop-agroforestry-fertilizer-weather-based interventions along with community participants as village climate risk management committees (VCRMCs), enriching overall village-level carbon building and reducing GHG emissions (Srinivasa Rao *et al*., 2016). These model villages are being replicated on a large scale in different states. For example, Maharashtra state replicated it in about 5000 villages. Village resilience to adverse weather improved by 10-15% with CRVs, and the mitigation potential of CRVs was recorded up to 25% (Dhakar *et al*., 2021). The carbon balance of 7 villages from Maharashtra state resulted in a net sink and contributed to the mitigation of GHGs to the extent of 1796 t CO_2 eq/year (Srinivasarao *et al*. 2016). The one-unit decrease in usage of N fertilizer may decrease the N_2O emissions by 0.09 times.

4. Road Map for Net Zero Carbon Commitment (NZCC)

Achieving net-zero carbon emissions demands a multifaceted and collaborative strategy spanning diverse sectors related to agriculture, from planning, crop season to post-production and value chains and involving numerous stakeholders. A focused roadmap is essential for guiding these efforts:

- Setting Clear Targets and Timelines
- Developing a Comprehensive Agriculture Mitigation Strategy
- Transition to Renewable Energy Sources in the Agri Sector
- Improving Production Efficiency
- Decarbonizing Transportation and Industry
- Promoting Sustainable Agriculture and Land Use

- Encouraging Sustainable Consumption and Lifestyle Changes
- Investing in Research, Development, and Innovation
- Collaborating and Engaging Stakeholders
- Monitoring, Reporting, and Adjusting

While specific priorities may vary, a coordinated approach addressing multiple sectors and involving various stakeholders is fundamental to effectively achieving net-zero carbon emission commitments.

5. Carbon Credits: Mechanisms and Implementation

The quantification of GHG in terms of tons of carbon dioxide (CO_2) equivalent removed from the atmosphere is represented by carbon credits. A carbon credit is gained for each ton of CO_2 or its equivalent that is kept out of the atmosphere. Carbon credits are significant because they serve as a mechanism based on the market to encourage reductions in emissions. Carbon credits provide a market where people who release greenhouse gas emissions have a financial incentive to lower their emissions by placing a monetary value on carbon emissions. In order to offset their remaining emissions, entities that cannot completely reduce their emissions might buy carbon credits simultaneously. Because it allocates funds to initiatives with the biggest potential to lower overall GHG levels, this mechanism makes emission reductions more affordable. Thus, carbon credits are essential in the global effort to mitigate climate change by reducing GHG emissions. Therefore, understanding carbon credits, their mechanisms, and implementation strategies is crucial for achieving the net carbon commitment goal. The success of implementing carbon trading will rely on: (i) developing robust regulatory mechanisms, (ii) promoting green finance and investment for creating enabling infrastructure, (iii) capacity building and awareness, and (iv) encouraging sector-specific programs. Henceforth, to fulfill the Net Zero commitments on GHG emissions using carbon credits India may access both domestic and international markets to finance projects aimed at reducing emissions through institutions such as the CDM and the VCM. India can accomplish its emissions reduction targets, promote sustainable development, and participate in global climate action by adopting carbon credits and incorporating them into its climate plan.

6. Net Zero Commitment Targets

6.1. Awareness and capacity building

A comprehensive strategy for raising awareness and developing capability is needed to meet Net Zero objectives for GHG emissions in India. This strategy's key elements include public awareness campaigns, instructional initiatives in schools, specialized training for farmers and industry, and government officials' capacity building. India needs to prioritize comprehensive awareness and capacity-building activities to meet its Net Zero targets on GHG emissions. At the National and State levels, capacity-building training institutes should have a carbon and mitigation-sensitive curriculum module. Regional-level climate action policy and capacity building are essential to meet the agriculture sector mitigation targets. In addition, policymakers and government representatives must possess the knowledge and abilities necessary to create and carry out successful climate policies by relevant ICAR institutions.

6.2. Catalyzing innovations

India needs to concentrate on igniting innovation in several industries to meet its promise of achieving Net Zero GHG emissions in Indian agriculture. Innovation is essential to create and implement technology that can drastically cut emissions and advance sustainable practices. Funding research and development (R&D) for energy-efficient concentrate feed, green fodder systems, vaccination, and shelter management systems in the livestock systems is critical. Efficient paddy systems with less water, biofertilizers, less and efficient formulations of plant nutrients, direct-seeded rice, and more promising innovations are currently being carried by many agri-startups. Climate-smart agriculture and encouraging the use of renewable energy in agriculture can help cut emissions. This involves providing funds and assistance to R&D centers, new businesses developing energy storage, carbon capture and storage (CCS), and renewable energy technology (IEA, 2023).

6.3. Multi-ministerial collaborations

Effective multi-ministerial cooperation across various industries is needed to guarantee that policies and initiatives align with the Net Zero objectives of the agriculture sector. Ministries that oversee things like the environment, rural development, energy, agriculture & farmers' welfare, animal & fisheries, *Jalashakti*, transportation, and finance must collaborate closely towards mitigation targets of agriculture and associated sub-sectors. Joint working groups, task forces, and frequent discussions to incorporate climate considerations into sectoral policy can help to facilitate this collaboration (MoEFCC, 2022). This calls for a coordinated strategy in which ministries collaborate to achieve shared objectives and ensure that policies reinforce one another and aid in shifting to a low-carbon economy (NITI Aayog, 2020). Creating a central hub for information exchange, monitoring, and data gathering on energy use, GHG emissions, and climate consequences can help policymakers make informed decisions.

6.4. NAPCC and SAPCC synergy

Effective coordination between the National Action Plan on Climate Change (NAPCC) and State Action Plans on Climate Change (SAPCC) is necessary for India to meet its promise to achieve net-zero greenhouse gas emissions from the agriculture sector. Their aims and strategies must be integrated and aligned. With eight missions concentrating on various areas like solar energy, energy efficiency, and sustainable agriculture, the NAPCC, which was established in 2008, offers a thorough framework for addressing climate change at the national level. National Mission on Sustainable Agriculture (NMSA) aims to implement the best agricultural practices across India, covering natural resource management, integrated farming systems, and soil health management. However, each state creates its own SAPCC to address its unique climate objectives and issues. Ensuring alignment between the general objectives of the NAPCC and the aims and priorities of SAPCCs is crucial for fostering synergy. Also, it is crucial that state and federal governments have structures for cooperation and coordination. Regular consultations, collaborative working groups, and the exchange of best practices and lessons discovered are all examples of this. The federal government can help states implement their SAPCCs by offering financial support, technical help, and capacity building. The NAPCC and SAPCCs may work together to create strong relationships and synergies, which would provide a coherent strategy for India's transition to net-zero emissions in the agri-sector. In addition, utilizing every state's advantage and distinctive qualities can help create a more successful climate action framework. States need specialized solutions since they have different ecosystems, resources, and vulnerabilities. States with substantial coastal areas, for instance, would prioritize conserving mangroves and building climate-resilient agri-infrastructure, whereas states with an abundance of solar/wind energy potential, which might be utilized in the agri warehouses, storage, and food processing industries (MoEFCC, 2023). India can fully utilize its states in the pursuit of Net Zero emissions by incorporating these various techniques into the national framework.

6.5. Rural Institutions and FPO

It is imperative to support and strengthen rural institutions like Self-Help Groups (SHGs) and Panchayati Raj Institutions (PRIs). These organizations are essential for encouraging community mobilization and adopting sustainable agricultural practices with significant potential for GHG reduction. By fortifying these rural institutions, India can lay a solid foundation for sustainable rural development and carbon reductions. In order to achieve Net Zero emissions, Farmer Producer Organizations (FPOs) must be encouraged and supported. Smallholder farmers can use FPOs as a platform to access markets, technology, and resources for sustainable agriculture. Value addition, post-harvest management, and climate-resilient farming techniques can be the main areas for capacity-building initiatives for FPO members (Singh *et al*., 2023).

6.6. Finance and PPP

Raising funds for climate action is imperative. This involves enticing investments from the private sector by means of financial incentives, regulatory frameworks, and risk-sharing arrangements. Creating green finance instruments, like carbon markets, green bonds, and green loans, can help money move toward environmentally friendly initiatives (Sartzetakis, 2021). Furthermore, funding for climate adaptation and mitigation initiatives in the agriculture sector might be obtained by creating specialized climate funds at the federal and state levels. In order to accelerate climate action, it is imperative to promote Public-Private Partnerships (PPPs). Corporate Social Responsibility (CSR) funds for mitigation research and ground-level implementation are a good way forward. To undertake sustainable initiatives, PPPs can combine public and private sector knowledge, assets, and creativity. PPPs, for example, can be used to create climate-resilient agriculture programs, sustainable infrastructure projects, and bio-energy projects (NAAS Policy on PPP 2024). In order to ensure transparency, accountability, and risk-sharing in PPPs, it is imperative to establish unambiguous policy frameworks and regulatory systems.

7. Road Map for Net Zero Carbon Commitment

To achieve the net zero carbon commitment, mitigation technologies must be prioritized for different agri-production zones of India. Table 3 presents priority technologies towards NZCC in different regions.

Table 3. Priority technologies for implementation towards Net Zero Carbon Commitment in India.

Total Agriculture Emissions Target Reduction = 461 MtCO2e							
Livestock Emissions (58% Current Emissions)	**Crop Production Emissions, Paddy, Fertilizer Broadcasting, Crop Residue Burning, Manure, Intensive Tillage, Water Lifting Energy, Zoom Lands, Flood Irrigation Systems, Land Degradation etc. (42% of Current Emissions)**						
Priority Technology and States/Ecosystems							
Green Fodder Feed Concentrate Shelter and Hygiene Tolerant and high yielding breeds	DSR & Efficiency Paddy Systems (Punjab & Haryana)	Residue into Biogas Energy and Manure (Target 300 Mt Crop Residue)	Low Tillage Systems & Legume Cover Crops (20 Mha)	Biochar (crops and Vegetable waste) (100 Mt) (One Third of Field Burned Residue)	Fertilizers, Fertigation and Organic Farming, Efficient Water Lifting Motors	Agro-forestry (10 Mha) and Rehabilitation of Degraded Lands, Zoom Lands; Tank Silt (30 Mha)	Horticulture & Perennial Crops with low Tillage and Cover Crops (10 M ha)
UP, AP, MP, Maharashtra. Rajasthan, West Bengal, and other High Intensity Livestock States	IGP Telangana, AP, West Bengal, Eastern India	Rainfed States IGP	Punjab, Haryana, UP, Rainfed States, Karnataka, Maharashtra, Rajasthan, AP, Telangana, Tamil Nadu, MP	Punjab, Haryana, UP, AP, Telangana, Maharashtra, Karnataka	Telangana, AP, Maharashtra, Punjab, Haryana, Western UP (Covering rainfed dry lands; high Fertilizer application)	Irrigated & Rainfed States NEH Himalayan States	Maharashtra AP, Telangana, Karnataka, HP, UP

The above technologies are being implemented in several central and state governments at different levels. Shifting one-third of the rice area (about 15 M ha) in the next 23 years (during *Amrit kaal*) to DSR and water-nutrient efficiency rice systems can reduce the larger share of CH4 and N2O emissions from the agriculture sector. Crop diversification program in paddy area leads to a reduction in water and fertilizer application. About 10 M ha horticulture and perennial systems can be utilized to implement conservation agriculture, cover crops in inter rows, fertilization and organic production are proven technologies to offset carbon emissions. Organic farming looks for no-synthetic fertilizers and pesticides; neem-coated urea usage, granular nutrients and precision nutrient management practice implementation contribute to improved fertilizer use efficiency, lowering nutrient application. These practices are implemented through the soil health mission and various fertilizer nutrient policies and programs. Biochar is a big opportunity towards NZCC and needs to move towards an agri-entrepreneurship model for wider adaptation, which can potentially convert about one-third of the crop residue currently burned in the field. Huge vegetable and fruit wastage is another opportunity for a business model of biochar making. There is a huge gap in land cover as per the forest policy, where the national agroforestry mission greatly contributes towards long-term carbon fixation and offsetting carbon emissions. Tree fodder systems could reduce methane emissions by contributing green fodder to livestock. Various livestock-related programs like Gokul Mission, Fodder Systems and Animal Health Schemes showed to be potential to have lesser methane emissions besides improving milk and meat yield. Prime Minister Krishi Sichai Yojan (PMKSY) contributes to the country's production efficiency and food production targets by expanding the irrigation area. Fertigation is an important technology for efficient nutrient and water use in major rainfed dryland states like Rajasthan, Maharashtra, AP, Telangana, Karnataka, Tamil Nadu, and MP. It was proven to be highly beneficial in horticulture crops. Integrated Farming System (IFS) in smallholder farming systems with circular carbon economy contributing to low-energy food production systems.

8. Policy Recommendations

8.1. Climate education

- Inclusion of climate education at all levels is a critical step towards fulfilling India's Net Zero objectives on GHG emissions. This entails incorporating lessons on sustainability and climate change into the curricula of all educational levels, from primary to postsecondary.

- The National Council of Educational Research and Training (NCERT) should create guidelines and materials to guarantee thorough teaching of climate science, responsible consumption, renewable energy, waste management, and sustainable agriculture.
- Programs for teachers to continue their professional development on climate change issues are also crucial. Teachers should have access to training workshops, seminars, and materials to improve their knowledge of climate science and efficient teaching techniques. This will help them to promote a sustainable and eco-friendly culture in schools and effectively communicate issues related to climate change.
- By prioritizing climate education, India can equip its youth with the necessary knowledge and awareness to contribute to a sustainable and net-zero future.
- Efforts are needed to educate the society about responsible consumption and living in harmony with the environment (Lifestyle for Environment, LiFE)
- New comprehensive courses need to be introduced at the higher education level to fully understand climate change and climate action.

8.2. Research

- Research and development (R&D) in green energy technology and sustainable intensification practices in agriculture should be prioritized.
- It is essential to fund R&D for renewable energy sources, including solar, wind, and biofuels.
- Supporting research on low-carbon transportation methods, waste management techniques, and sustainable agriculture practices is important.
- Collaboration between academic institutions, industry, and governmental organizations (AIGs) is essential, which leads to collaborative research and technology transfer in PPP mode in climate mitigation research in the agriculture sector.
- Multidisciplinary research programs that tackle the intricate problems of climate change and the energy transition should receive funding and support.

8.3. Government programs and schemes

- Incorporating net carbon concerns into the development agenda and initiatives is crucial for India to meet its Net Zero pledges on GHG emissions. This entails integrating industrial development, urban planning, and infrastructure projects related to agri and allied sector with carbon accounting and mitigation strategies.
- All the projects should be required by law to evaluate their carbon footprints, and the implementation of carbon offset programs should be a requirement as well. This will guarantee that new agri-infrastructure, such as energy-efficient warehouses, environmentally friendly transit, and green areas, is planned using low-carbon principles.
- Policies and incentives should also be first to support net carbon projects across the agro-industrial sector. This involves providing tax breaks or other financial aid to businesses that employ net carbon strategies, like making investments in green and bio-energy sources or implementing carbon capture systems.
- The development of carbon offset initiatives like green fodder initiatives, biochar, and agroforestry, and the building up of village institutions for GHG mitigation such as Farmer-Producing Organizations (FPOs) or Common Interest Groups (CIGs) with PPP besides government schemes, such as RKVY, MGNREGA, etc.

8.4. Innovation and start-ups

- Building up innovations rapidly in mitigating potential agri-startups towards crop and input loss, market, storage, processing, and reducing food loss.
- The government should promote agri-entrepreneurs working on efficient system productivity, input loss minimization, energy efficiency, and carbon capture technology with money, incubation assistance, and regulatory incentives to foster an environment that is favorable to innovation. This includes creating venues and innovation hubs where entrepreneurs may network, get mentorship, and present their ideas.
- Furthermore, establishing public-private partnership platforms might help to accelerate the implementation of creative fixes. These platforms can facilitate collaboration on pilot projects and the scaling up of successful initiatives between government agencies, private sector enterprises, agriculture research institutes, and agri-startups.

- The government might also support open agri-innovation contests and challenges to encourage innovation and find viable approaches to cutting emissions in the agriculture sector.

8.5. Government support policies

- The government ought to create and carry out bold, well-defined policies that facilitate the shift to a low-carbon economy by establishing precise goals for lowering emissions with regenerative agricultural practices with larger mitigation potential.
- The government needs to incentivize low-carbon technology adoption by farmers.
- Policies that offer tax benefits, grants, and subsidies should encourage industries to invest in sustainable agri-technologies and innovations.
- Regulations should also be implemented to uphold emissions regulations and encourage environmentally friendly practices at the village and farm levels with incentive support.
- Stability and long-term planning should also be priorities for policy frameworks. Policies must remain consistent to provide businesses and investors with the assurance they need to commit to sustainable operations in agriculture, livestock, horticulture, poultry, fishery, and agroforestry.
- The government should also regularly evaluate and change its regulations to keep up with changing technology developments and international climate goals.

India has already launched various programs to meet the zero-carbon emission targets. The targets should be met before the deadline. The future action plan will require a comprehensive approach of effective technologies, enabling policies, inclusive institutions and required infrastructure by engaging all the stakeholders with sufficient funding mechanism.

9. References

Bhattacharyya, P. (2022). Climate smart agriculture: Special reference to conservation agriculture. In Conservation agriculture and climate change (pp. 21–32). CRC Press.

Bhushan, C., Banerjee, S., & Agarwal, S. (2020). Fighting COVID-19 climate change battle: Mitigation and adaptation policies for India. Centre for Science and Environment.

Bijay-Singh, Yadvinder-Singh, Parihar, C. M., Jat, M. L., Pradhan, S., & Pooniya, V. (2020). Leaf colour chart for nitrogen management and yields of irrigated rice in north-western India. Nutrient Cycling in Agroecosystems, 116(1), 1–16. https://doi.org/10.1007/s10705-019-10027-0

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235–239. https://doi.org/10.1038/nature15725

Compston, H. (2018, June 7). The costs of climate change: A derelict mining town with $2 trillion in rehabilitation costs is a warning to us all. ABC News. https://www.abc.net.au/news/2018-06-07/costs-of-climate-change-could-be-catastrophic/9838994

Chand, R., & Singh, J. (2023). From green revolution to amrit kaal. National Institution for Transforming India, Government of India.

Dhakar, R., Hooda, P., Solanki, K. R., Karthik, V., & Srinivasa Rao, C. (2021). Climate resilient village (CRV) model: A novel approach for climate change adaptation and mitigation. Current Science, 120(6), 1035–1047. https://doi.org/10.18520/cs/v120/i6/1035-1047

Dhyani, S. K., Newaj, R., & Sharma, A. R. (2009). Agroforestry: Its relation with agronomy, challenges and opportunities. Indian Journal of Agronomy, 54(3), 249–266.

Food and Agriculture Organization of the United Nations (FAO). (2020). Climate-smart agriculture: Enhancing resilient agricultural practices, food security and nutrition. FAO. http://www.fao.org/climate-smart-agriculture/en/

Food and Agriculture Organization of the United Nations (FAO). (2024). Climate-smart agriculture sourcebook. https://www.fao.org/climate-smart-agriculture-sourcebook/about/en/

Government of India. (2011). National Mission for a Green India (Under the National Action Plan on Climate Change). Ministry of Environment and Forests.

Government of India. (2022). India's updated nationally determined contribution (NDC). UNFCCC. https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20NDC.pdf

Goyal, R., & Aggarwal, A. (2021). India's participation in the voluntary carbon market: Opportunities and challenges. Renewable and

Sustainable Energy Reviews, 138, 110535. https://doi.org/10.1016/j.rser.2020.110535

Hamrick, K., & Gallant, M. (2017). Unlocking potential: State of the voluntary carbon markets 2017. Forest Trends' Ecosystem Marketplace. https://www.forest-trends.org/publications/unlocking-potential/

Hernwal, D. S., Balasubramanian, D., & Aravindakshan, S. (2023). A guide book on local climate change adaptation planning and implementation: A primer for the Panchayat Raj Institutions. Arunachal University of Studies. https://cgspace.cgiar.org/handle/10568/38153

International Energy Agency (IEA). (2023). Net zero roadmap: A global pathway to keep the 1.5°C goal in reach (2023 Update). https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf

Indian National Committee on Irrigation and Drainage (INCID). (1994). Drip irrigation in India. CBIP.

Indian National Committee on Irrigation and Drainage (INCID). (1998). Sprinkler irrigation in India: Status, prospects and recommendations. CBIP.

Intergovernmental Panel on Climate Change (IPCC). (2014). Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (R. K. Pachauri & L. A. Meyer, Eds.). IPCC.

Intergovernmental Panel on Climate Change (IPCC). (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (V. Masson-Delmotte *et al*., Eds.). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

Intergovernmental Panel on Climate Change (IPCC). (2022). Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (H.-O. Pörtner *et al*., Eds.). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/

Ministry of Environment, Forest and Climate Change (MoEFCC). (2015). India's intended nationally determined contribution (INDC). Government of India. https://moef.gov.in/wp-content/uploads/2020/03/INDC-MoEF-Final-3rd-March-2015.pdf

NCERT. (n.d.). Syllabus at elementary level. https://ncert.nic.in/pdf/publication/syllabus/syllabus_elementary_level.pdf

Jain, N., Dubey, R., Dubey, D. S., Singh, J., Khanna, M., Pathak, H., & Bhatia, A. (2014). Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic Plains. Paddy and Water Environment, 12(2), 355–363.

Jain, R., Kaur, A., Thakur, S., & Srivastava, V. K. (2021). Automated irrigation system for banana crop in India using Internet of Things. Computers and Electronics in Agriculture, 180, 105930. https://doi.org/10.1016/j.compag.2020.105930

Jat, M. L., Dagar, J. C., Sapkota, T. B., Singh, Y., Govaerts, B., Ridaura, S. L., Saharawat, Y. S., Sharma, R. K., Tetarwal, J. P., Jat, R. K., & Hobbs, P. (2016). Climate change and agriculture: Adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. Advances in Agronomy, 137, 127–235. https://doi.org/10.1016/bs.agron.2015.12.005

Kumar, V., Singh, A. P., Singh, B. P., Kumar, B., Kumar, V., Pandey, D., & Singh, R. K. (2015). Nitrogen use efficiency of neem coated urea in transplanted rice under different planting techniques. The Bioscan, 10(4), 1573–1578.

Mazumdar, D., Kumar, V., Ghoshal, N., Bhar, I. S., Yadav, R. L., & Pandey, C. S. (2000). Neem-coated urea for increasing nitrogen use efficiency and productivity of lowland rice. Nutrient Cycling in Agroecosystems, 59(3), 271–276. https://doi.org/10.1023/A:1017592323358

Ministry of Environment, Forest and Climate Change, Government of India. (2021). India's updated nationally determined contribution (NDC) to the Paris Agreement. https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20NDC.pdf

Ministry of Environment, Forest and Climate Change, Government of India. (n.d.). Clean Development Mechanism. Retrieved from https://cdm.moefcc.gov.in/

Ministry of Environment, Forest and Climate Change, Government of India (MoEFCC). (2020). India's intended nationally determined contribution: Working towards climate justice. MoEFCC, New Delhi.

Ministry of Environment, Forest and Climate Change, Government of India (MoEFCC). (2021). Capacity building on climate change. MoEFCC, New Delhi. https://moef.gov.in/en/capacity-building/

MoEFCC. (2022). India's long-term low-carbon development strategy. https://moef.gov.in/wp-content/uploads/2022/11/Indias-LT-LEDS-2.pdf

MoEFCC. (2023). Ministry of Environment, Forest and Climate Change, Government of India. http://moef.gov.in/moef/division/environment-divisions/climate-changecc-2/documents-publications/index.html

Mrunalini, K., Behera, B., Jaraman, S., Abhilash, P. C., Dubey, P. K., Narayanaswamy, G., Prasad, J. V. N. S., Rao, K. V., Krishnan, P., Pratibha, G., & Srinivasarao, C. (2022). Nature-based solutions in soil restoration for improving agricultural productivity. Land Degradation & Development. https://doi.org/10.1002/ldr.4207

Narayanamoorthy, A. (2006). Potential for drip and sprinkler irrigation in India. In Proceedings of the 7th Annual Partners' Meet: Synthesis of Discussions and Recommendations (IWMI-TATA Water Policy Research Program). ICRISAT Campus, Patancheru, India.

National Council of Educational Research and Training (NCERT). (2017). Syllabus for classes at the elementary level. NCERT, New Delhi.

National Institute of Agricultural Extension Management (MANAGE). (2018). Training programs on climate resilient agriculture. MANAGE, Hyderabad. https://www.manage.gov.in/training/climateresilient.asp

National Research Center for Agroforestry (NRCAF). (2007). Perspective plan vision 2025. Jhansi: NRCAF.

Nayak, A. K., Shahid, M., Nayak, A. D., Dhal, B., Moharana, K. C., Mondal, B., ... & Tripathi, R. (2019). Effects of different nitrogen fertilizers and their application rates on soil health and greenhouse gas emissions from a sub-humid tropical rice field. Geoderma, 355, 113906. https://doi.org/10.1016/j.geoderma.2019.113906

Olsen, K. H. (2007). The clean development mechanism's contribution to sustainable development: A review of the literature. Climatic Change, 84(1), 59–73. https://doi.org/10.1007/s10584-007-9267-y

Pathak, H. (2015). Greenhouse gas emission from Indian agriculture: Trends, drivers and mitigation strategies. Proceedings of the Indian National Science Academy, 81(5), 1133–1149.

Pathak, H., Sahrawat, K. L., Kassam, A. H., Rehman, H., & Srinivasa Rao, C. (2021). Sustainable food and nutrition security through resilient farming systems and practices. In Climate change and resilient food systems (pp. 1–34). Springer, Singapore. https://doi.org/10.1007/978-981-15-9458-0_1

Prasad, J. V. N. S., Srinivasarao, C., Srinivasa, K., Naga Jyothi, C., Venkateswarlu, B., Ramachandrappa, B. K., Dhanapal, G. N., Ravichandra, K., & Mishra, P. K. (2016). Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi-arid tropics of southern India. Soil & Tillage Research, 156, 131–139.

Ramappa, K. T., & Manjunatha, B. L. (2019). Effect of neem coated urea on growth, yield and nutrient uptake of different crops. International Journal of Current Microbiology and Applied Sciences, 8(6), 2545–2550. https://doi.org/10.20546/ijcmas.2019.806.305

Rizvi, R. H., Dharumarajan, S., Lalljee, B., & Singh, R. (2021). Agroforestry for climate resilience and rural livelihood: Key perspectives from India. Agroforestry Systems, 95(4), 687–705. https://doi.org/10.1007/s10457-021-00603-4

Samra, J. S., & Srinivasa Rao, Ch. (2021). Circular carbon economy in India: Efficient crop residue management for harnessing carbon, energy and manure with co-benefits of greenhouse gases (GHGs) emissions mitigation (Policy Paper). ICAR–National Academy of Agricultural Research Management, Hyderabad, India.

Sapkota, T. B., Vetter, S. H., Jat, M. L., Sirohi, S., Shirsath, P. B., Singh, R., Jat, H. S., Smith, P., Hiller, B., & Stirling, C. M. (2018). Cost-effective opportunities for climate change mitigation in Indian agriculture. Science of the Total Environment. https://doi.org/10.1016/j.scitoteenv.2018.11.225

Sartzetakis, E. S. (2021). Green bonds as an instrument to finance low carbon transition. Economic Change and Restructuring, 54(3), 755–779.

Sharma, S. K., Singh, S., Mishra, V. K., Singh, A. K., Yadav, D. S., & Manpotra, S. (2022). Soil health card and soil testing: A study on their impact on fertilizer consumption in India. Soil Use and Management, 38(2), 637–652. https://doi.org/10.1111/sum.12762

Singh, D.P., Singh, R., Kumari, S., Singh, J.P., Bhaskar, R., & Kumar, V. (2016). Effect of neem-coated urea and conventional urea on yield, nutrient uptake and nitrogen use efficiency in sugarcane and cotton. Sugar Tech, 18(4), 385-391. https://doi.org/10.1007/s12355-015-0399-3

Singh, S. K., Devi, R., Tomar, S. P., Srivastava, D. S., Singh, A., & Singh, S. K. (2023). Challenges faced by farmer producer organizations and suggested policy reforms.

Siraj, K., Dharumarajan, S., Kaleeswaran, S., Srinivasan, R., & Maity, A. (2022). Climate-smart agriculture: A pathway to ensure food and nutritional security under changing climate scenarios. Ecological Indicators, 138, 108810. https://doi.org/10.1016/j.ecolind.2022.108810

Srinivasa Rao, Ch., Rao, K. V., Gopinath, K. A., Prasad, Y. G., Arunachalam, A., Ramana, D. B. V., Ravindra Chary, G., Gangaiah, B., Venkateswarlu, B., & Mohapatra, T. (2020). Agriculture contingency plans for managing weather aberrations and extreme climatic events: Development, implementation and impacts in India. Advances in Agronomy, 159. https://doi.org/10.1016/bs.agron.2019.08.002

Srinivasa Rao, Ch., Gopinath, K. A., Prasad, J. V. N. S., Prasannakumar, & Singh, A. K. (2016). Climate resilient villages for sustainable food security in tropical India: Concept, process, technologies, institutions, and impacts. Advances in Agronomy, 140(3), 101-214.

Srinivasa Rao, Ch., Venkateswarlu, B., Lal, R., Singh, A. K., & Kundu, S. (2013). Sustainable management of soils of dryland ecosystems of India for enhancing agronomic productivity and sequestering carbon. Advances in Agronomy, 121, 253-329.

Srinivasa Rao, Ch., Lal, R., Kundu, S., Prasad Babu, M. B. B., Venkateswarlu, B., & Singh, A. K. (2014). Soil carbon sequestration in rainfed production systems in the semiarid tropics of India. Science of the Total Environment, 487, 587-603.

Srinivasarao, Ch., Singh, S. P., Kundu, S., Abrol, V., Lal, R., Abhilash, P. C., Chary, G. R., Thakur, P. B., Prasad, J. V. N. S., & Venkateswarlu, B. (2021). Integrated nutrient management improves soil organic matter and agronomic sustainability of semiarid rainfed Inceptisols of the Indo-Gangetic Plains. Journal of Plant Nutrition and Soil Science. https://doi.org/10.1002/jpln.202000312

Srinivasarao, Ch., Prasad, R. S., & Mohapatra, T. (2019). Climate change and Indian agriculture: Impacts, coping strategies, programs and policy. Technical Bulletin/Policy Document. Indian Council of Agricultural Research, Ministry of Agriculture and Farmers' Welfare and Ministry of Environment, Forestry and Climate Change, Government of India, New Delhi. p. 25.

Swartz, J. (2016). The voluntary carbon market: Explaining the rules and reviewing the supply. Journal of Environmental Investing, 7(1), 14-26.

The Energy and Resources Institute (TERI). (2022). Training programs on sustainable manufacturing and green industries. TERI, New Delhi. https://www.teriin.org/capacity-building

The JEI. (n.d.). The voluntary carbon market: Explaining the rules and reviewing the supply. https://www.thejei.com/the-voluntary-carbon-market-explaining-the-rules-and-reviewing-the-supply/

UNESCO. (2019). Education for sustainable development: A roadmap. United Nations Educational, Scientific and Cultural Organization. https://unesdoc.unesco.org/ark:/48223/pf0000374794

United Nations Climate Change. (n.d.). The Paris Agreement. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

United Nations Framework Convention on Climate Change (UNFCCC). (2015). Adoption of the Paris Agreement. FCCC/CP/2015/L.9/Rev.1. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (n.d.). What is the clean development mechanism? Retrieved from https://unfccc.int/process-and-meetings/the-kyoto-protocol/mechanisms-under-the-kyoto-protocol/the-clean-development-mechanism

Venkateswarlu, B., Srinivasarao, Ch., Srinivasa Rao, M., Vijayasankar, B., & Sudhir, P. (2021). Climate resilient agriculture: An overview. Indian Journal of Agronomy, 66(1), 1-14.

9 Circular Agricultural Economy

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1. Context

Given the projected one-third increase in world population by 2050, best estimates indicate a need to increase agricultural and food production by two-thirds by 2050 to feed an additional 2 billion people to adequate nutrition levels and other requirements such as fibre, feed, fuel, fertilizers, etc. The problem is further compounded by food loss and waste, estimated to be around 35%, as well as the impacts of climate change on agricultural systems; higher temperatures and changes in global precipitation patterns increase the likelihood of reductions in crop yields and the proliferation of weeds and pests on agricultural land. These situations lead to the intensification of agriculture and the over-exploitation of all resources.

In addition to the above challenges, repetitive disruption of essential supply chains due to global conflicts and a COVID-19-like pandemic cannot be ruled out, and therefore, countries are nudging to adopt and promote sustainable circular bio-economy models to become as independent as possible from events outside defined boundaries. In general, the circular economy is a model of production and consumption that focuses on designing products that are more durable, reusable, repairable and recyclable to extend their lifetime and reduce waste and fulfil as many needs as possible, whether financial or physical, from within the defined geographical boundaries. Circular economy describes input and output systems that complement each other based on business models. In this model, the "end of life" concept is made absent by reusing and recycling

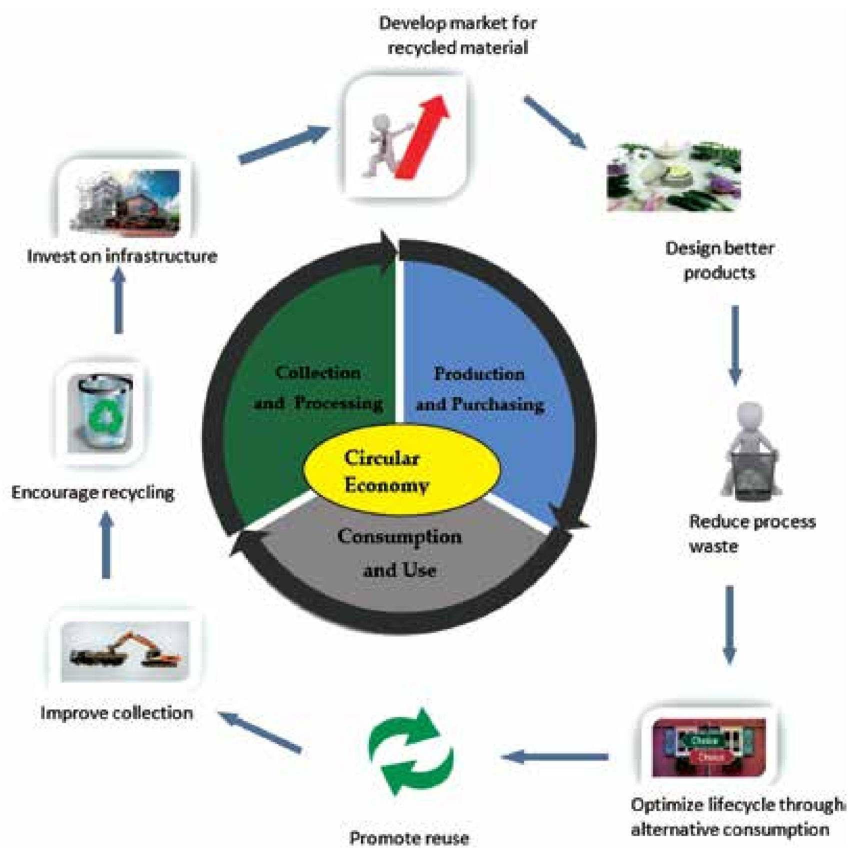
[1] Indian Council of Agricultural Research, New Delhi

[2] ICAR-Central Institute of Post Harvest Engineering & Technology, Ludhiana

[3] ICAR-National Institute of Secondary Agriculture, Ranchi

materials in production, processes and their distribution for consumption in one or the other form in the same system (Fig. 1).

Figure 1. *Concept of circular economy.*



The concept of circular economy includes an extension of a product's life cycle, minimizing waste and adding value. It functions on micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation, global level) to achieve sustainable development. This implies the development of a high-quality environment, economic prosperity and social equity, for the benefit of current and next generations.

With reference to agriculture, this approach is characterized as a circular bioeconomy. The circular bioeconomy includes waste streams from renewable bio-resources (including abundant biomass left over after extracting useful products from agriculture) to be looped back for recycling or conversion from matter to energy by innovative biological production processes. An integral analysis of the agri-food value chain, including crop, livestock and fisheries production, food processing and retail sector, is required to provide mechanisms to achieve an increase in the recycling and valorization of agricultural waste by maximizing the use of by-products and co-products via the creation of new sustainable value chains.

The chapter aims to identify the relevant agro-based sectors in which circular economy tools can be introduced more easily and provide information about the importance of the transition to a circular economy. It elaborates on the R&D needs for faster development, offering solutions to problems such as managing secondary raw materials (including waste), the need for resource and energy independence, and environmental security.

2. Challenges, Opportunities and Approaches for Implementing the Circular Economy

2.1. Challenges

To achieve sustainability and resilience, a critical area that should be addressed in India is the management of municipal, industrial, and agricultural wastes in both urban and rural areas. Agricultural wastes, including crop and animal residues, are often burned in the fields or used as traditional household fuels in rural areas. These practices are almost always associated with uncontrolled combustion and result in severe pollution of air, soil and water, creating health problems for both workers and nearby living beings. Much of this residue could be beneficially used with better efficiency as a renewable energy source or materials of higher commercial value. Generally, recycling and composting programs cannot keep pace with waste growth.

The challenges of modernizing waste collection, segregation, treatment and disposal are enormous. Following the establishment of the Swachh Bharat (Clean India) Mission in 2014, a series of stringent rules have been enforced since 2016 for solid waste management, including specific requirements for plastic wastes, electronic wastes, construction and demolition debris, biomedical wastes, and hazardous wastes. However, despite these regulatory efforts, the Indian economy will continue to generate growing waste streams due to increased population, urbanization, crops and livestock residues, significantly impacting human health and the environment. Beyond the obvious concerns about waste proliferation, improved waste management is important for controlling a substantial source of greenhouse gases (GHGs)—methane emissions from landfills, as well as nitrous oxide and methane from agricultural waste combustion. Moreover, material throughput is a major driver of GHG emissions, and hence waste reduction will significantly decrease energy and material demand and the associated GHG emissions throughout global supply chains (Fiksel, 2011).

There are many barriers to adopting/implementing the circular economy (CE) concept, such as a lack of appropriate technology, a lack of funding, inadequate financial resources and information, local customs and ethos, and laws and rules supporting the circular economy. In addition, the initial investment for industries to establish the required plant may be high. Within the market, demand for circular products and processes is still restricted, and consumers lack environmental awareness. In the private sector, there may be a lack of commitment at the management level and a shortage of qualified personnel to work with CE. Representatives of the industry and economy aren't sufficiently trained to introduce the new circular economy business models.

The waste management policy is currently inadequate and outdated, which causes problems in implementing the waste sector regulations. The awareness level about the potential of waste as a raw material is low, while the market for secondary raw materials is underdeveloped. This challenge is relevant to many stakeholders (government, regional and local authorities, population, academic communities, business communities, etc.), requires behavioral adjustments, reframing existing waste management systems and reorienting to the prevailing circular economy concepts. The research potential of the scientific community has not been sufficiently used to contribute to managing waste. There is also a lack of awareness about the circular design advantages in the production process. The knowledge and the level of information about the importance of circular economy digital platforms are underdeveloped.

Priority sectors for circular economy at the national level are yet to be defined in line with the Indian Government's priorities, infrastructural development and institutional capacities. This requires creating and harmonizing national planning documents, amendments of laws (in different sectors) and technical regulations, promotion of voluntary instruments, introduction of economic instruments aligned with budget planning, and development of monitoring mechanisms for implementing regulations that contribute to the sustainable use of resources.

2.2. Opportunities for the circular economy

The concept of "circular economy" as a strategy for waste elimination has been broadly adopted in developed countries. Companies have sought to achieve "zero waste" by finding uses for discarded materials and closing the loop in their supply network. Circularity not only offers economic benefits and reduces a company's ecological footprint but also increases both business and community resilience by reducing dependence upon scarce resources and long-distance supply chains.

In the agricultural sector, best management practices such as conservation agriculture, integrated nutrient management, and sustainable intensification, can increase soil resilience and restore the carbon pool, providing multiple benefits—greenhouse gas sequestration, improved water quality and conservation, decreased nutrient loss, reduced soil erosion, greater crop yields, and food and nutritional security.

India generates an estimated 750 Mt per year of agricultural waste, a large proportion of which can be composted and used as soil amendments. With judicious use of chemical fertilizers, this would eliminate the nutrient deficit in agricultural soils while sequestering carbon and improving the health of soil, plants, animals, people and the environment. Agricultural wastes can also be utilized as industrial raw materials; for example, rice husk ash is a valuable industrial raw material for steel, cement, and refractory bricks, and can also be used for wastewater treatment, thermal insulation, mortar and concrete production, soil amendment, and silica production. Similarly, bagasse from sugarcane can be used to generate energy. An Accenture study suggested that India can unlock approximately half-a-trillion dollars of economic value by 2030 (Accenture, 2015) through adoption of Circular Economy business models by a combination of strategies—reduction in wasted material and energy resources, improved utilization of products and capital assets, product life extension, and value recovery from waste streams (Fiksel *et al.*, 2021).

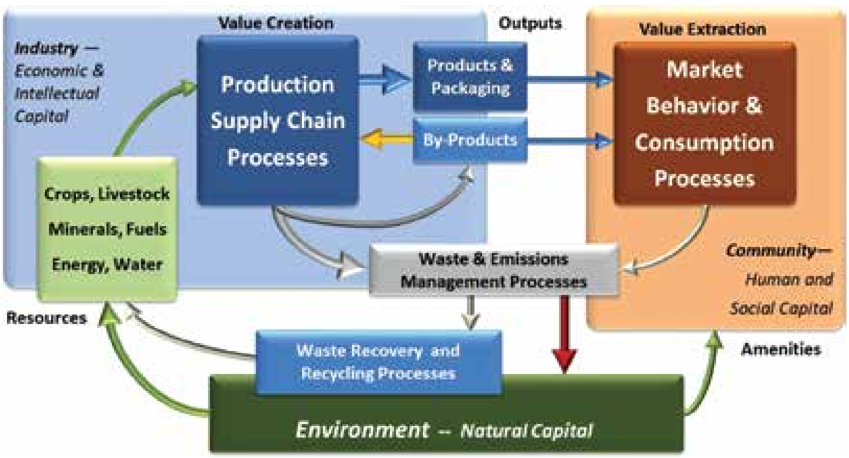
There are enormous opportunities for a circular economy in India. The country is likely to be a leading hub for technology and innovation. With its existing IT dominance and pool of tech talent, India is well-positioned to use digital technology to create innovative and cutting-edge circular businesses. This can potentially accelerate India to the forefront of the global circular economy revolution. India is one of the fastest-developing economies and can easily take up opportunities to use circular production methods and build sustainable designs. Several circular aspects are ingrained in Indian mindsets, like recycling of post-use materials, including agro-wastes at the household level, repair or extensive recovery of machines and materials, vehicle over-utilization, etc. Thus, this widespread cultural acceptance makes India a larger marketplace. The cost of providing services to consumers will be cheaper for those who take the circular path than for those who take the traditional 'take-make-dispose' model.

However, most of these activities take place in an informal way, providing the only source of livelihood for the poor. As the Indian middle class and the population in general are growing, these activities will become less attractive unless a more systematic policy approach is taken to professionalize them and move them up the value creation ladder.

2.3. Approaches for the circular economy

The implementation of circular economy requires a systematic approach that considers the broader economic, social and environmental systems in which commercial supply chains operate. Fig. 2 shows how a systems approach can be used to model the generation and disposition of wastes throughout the business value chain; this approach is based on the triple value framework, which explicitly maps the interdependencies among three types of dynamic systems—industries, communities, and the environment (Fiksel *et al.*, 2021). Resources are extracted from the environment, moving through production processes to create value for markets, and then the waste

Figure 2. *Circular economy processes.*



Source: *Fiksel et al. (2021)*

is disposed of or recycled. The lifecycle stages include extraction of raw materials from terrestrial sources, transport, processing, manufacturing and packaging into finished products, distribution and product support through various market channels, consumer use of products, and final disposal or recycling of residual wastes. These wastes are generated in solid, liquid, and gaseous forms, and may include hazardous pollutants and greenhouse gases. In this type of holistic analysis, it is important to account for direct consequences, such as financial benefits, as well as indirect or unintended consequences, including environmental and social impacts.

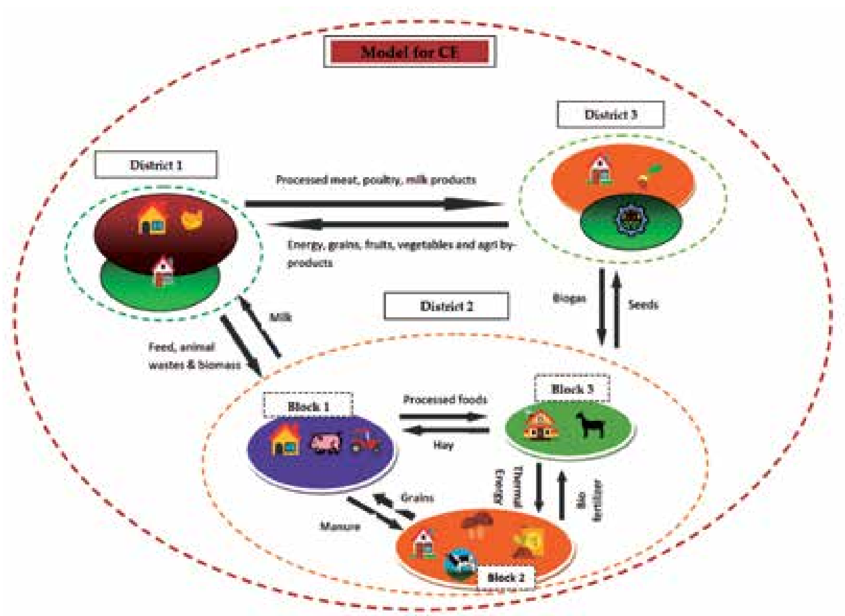
2.4. Digitalization and circular economy

Digitalization, including data and digital solutions such as digital platforms, smart devices, AI, internet of things and blockchain technologies, etc., is expected to have an important bearing on the development of the circular economy. Among other things, digitalization may be used for a more efficient deployment of natural resources, improved product design, production and consumption, reuse and repair of products, recycling, and waste management. At the same time, the necessary condition for a successful transition to circular economy is to establish continuous communication and firm collaboration between the different stakeholders (state, industry, consumers, waste industry), as well as to implement the complex technical solutions (product eco-design, recycling, repairs). Therefore, digitalization can provide the key contribution to the very process of transition to a circular economy. Products may contain an identifier (QR codes, RFID chips) that consumers or recyclers can scan in order to access the relevant product information, such as the presence of hazardous chemicals, or what to do when the product becomes waste. Production automation and recycling can increase efficiency and lower waste generation and energy consumption.

2.5. Model for circular economy at district level

A model for creating a circular economy at the district and block level and inter-district transactions is depicted in Fig. 3. Under each district, blocks can supply to and take from other nearby blocks the excess of agricultural produce, manure, processed food, biogas, etc. The districts having processing facilities may purchase and convert the raw material produced into different processed products and sell them to other districts. Facilities for collecting and processing waste materials need to be developed at every block level to efficiently recycle and reuse them. Similarly, renewable energy (either solar/wind/biomass based) can be generated at suitable locations and exchanged between districts.

Figure 3. *Circular economy model at district level.*



Many existing waste streams are underutilized. For example, municipal solid waste contains about 85% biomass and other combustible materials, comprising a mixture of energy-rich fuels. Likewise, coal combustion residues from power plants, such as fly ash, bottom ash, boiler slag, and flue gas desulfurization residues, can be beneficially used in concrete and cement production, structural fills, building products, gypsum wallboard, and surface stabilization.

The World Economic Forum estimates that, based on current technologies, the circular economy approach could save more than $1 trillion/year globally due to lower costs, lower carbon emissions, and supply chain risk reduction (WEF, 2013). Circular economy practices include reverse logistics (e.g., refurbishment of containers, pallets, used or defective products), beneficial reuse of wasted materials or energy (e.g., composting, used oil recovery, bio-digestion of organics, combined heat and power), and business model innovation (e.g., dematerialization, resource pooling, product-as-a-service).

A particularly effective circular economy practice is called by-product synergy (BPS), first introduced by the US Business Council for Sustainable Development and widely adopted by companies in diverse industries (Cimren *et al.*, 2010). By collaborating across industry lines, companies can avoid landfilling costs and reduce material procurement costs by converting industrial or municipal wastes into feedstocks for other industrial processes, thus turning waste into profit. This not only contributes to long-term sustainability by reducing a company's ecological footprint but also improves a company's resilience by reducing dependence on imported supplies and scarce resources. BPS is by far the shortest and most efficient path to achieving a circular economy.

3. Vision, Mission, and Objectives

Circular agriculture prioritizes minimal reliance on external inputs, emphasizing the closure of nutrient loops, soil regeneration, and environmental impact reduction. Widespread adoption of circular agriculture can potentially diminish resource demands and agricultural ecological footprints. Additionally, it facilitates reductions in land usage, agrochemical application, and waste generation, thereby contributing to global CO_2 emission mitigation.

By 2047, India aspires to become a *Vishwaguru* in agricultural science and innovation to attain sustainable food and nutritional security, improve the environment, and fulfil the commitment to net-zero carbon emissions. To develop a sustainable circular economy model in the field of agriculture and food by minimizing the use of non-renewable resources, reducing waste generation, and increasing waste reuse through methods like the repurposing of raw material waste. The following objectives need to be achieved.

- Increase residue reuse and recycling.
- Promote efficient use of materials, as well as the use of recycled materials.
- Help manage the carbon and water footprint more efficiently.
- Advance economic decarbonization to help find a way out of the energy crisis.
- Contribute to reducing our environmental impact.

4. Government Policies for Implementing the Circular Economy

In the transition towards a circular economy, the government should choose wisely and act as catalysts. Without the enabling conditions brought about by a public policy framework, the amount of circularity in India is likely to stagnate or even decline, as it is a feature of rapidly developing markets to move towards more linearity through more frequent replacement of assets due to increased spending power and economies of scale.

Several mature economies have passed legislation to support a circular economy, and the European Union (EU) has taken the lead with its Circular Economy package. Sweden is now giving tax breaks for repair activities (50% cut on VAT) and has passed a law that mandates retailers selling electronic goods to accept the same quantity of the goods they have sold, for reuse or recycling. Japan and the Netherlands, on the other hand, have also adopted strong Circular Economy Legislations. China has also passed a Circular Economy Promotion Law in 2009 for facilitating the circular economy through raising the resource utilization rate, protecting and improving the environment and promoting sustainable development.

The Government of India has been actively formulating policies and promoting projects to drive the country towards a circular economy. It has already notified various rules, such as the Plastic Waste Management Rules, e-Waste Management Rules, Construction and Demolition Waste Management Rules, Metals Recycling Policy, etc., in this regard. Direct initiatives were taken to address the challenges in using waste as a resource and to evolve a perspective on the recycling industry in India (Table 1).

To expedite the transition of the country from a linear to a circular economy, 11 committees have been formed—to be led by the concerned line ministries and comprising officials from MoEFCC and NITI Aayog, domain experts, academics and industry representatives—for 11 focus areas as mentioned below. The committees will prepare comprehensive action plans for transitioning from a linear to a circular economy in their respective focus areas. These will also carry out the necessary modalities to effectively implement their findings and recommendations.

The focus areas include the above 11 end-of-life products/recyclable materials/wastes that either continue to pose considerable challenges or are emerging as new challenge areas that should be addressed holistically.

5. Circular Agricultural Economy

The Agri-Food sector throughout the globe is facing the challenges of resources getting exhausted and raw material depletion. Each country is very much concerned about maintaining its complex agri-food systems by all possible means and using several of the latest technologies. The

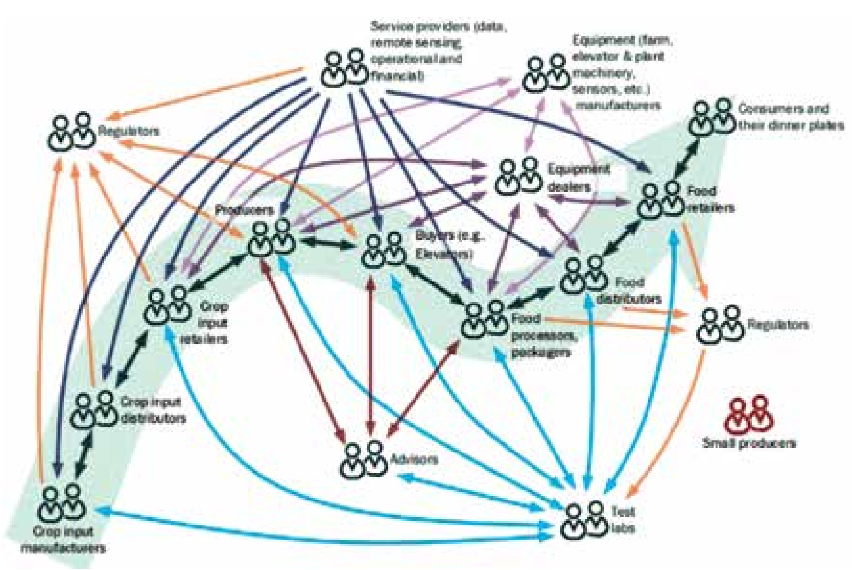
Table 1. End-of-life products/recyclable materials/wastes.

S. No.	Focus Area	Concerned Line Ministry
1	Municipal Solid Waste and Liquid Waste	Ministry of Housing and Urban Affairs
2	Agriculture Waste	Ministry of Agriculture and Farmers' Welfare
3	Electronic Waste	Ministry of Electronics and Information Technology
4	Lithium Ion (Li-ion) Batteries	NITI Aayog
5	Solar Panels	MNRE
6	Gypsum	Department for Promotion of Industry and Internal Trade
7	Toxic and Hazardous Industrial Waste	Department of Chemicals and Petrochemicals
8	Used Oil Waste	Ministry of Petroleum and Natural Gas
9	Scrap Metal (Ferrous and Non-Ferrous)	Ministry of Steel
10	Tyre and Rubber Recycling	Department for Promotion of Industry and Internal Trade
11	End-of-life Vehicles (ELVs)	Ministry of Road Transport and Highways

complexities of the Agri-food system can be assessed from Figure 4. The industry participants are therefore essential for sustainable solutions through natural and fossil fuel resource optimization methods. Natural and Agricultural resources-based circular economy (CE) is one of the steps towards that direction for a defined boundary.

India is one of the global agricultural powerhouses. Agriculture, with its allied sectors, is India's largest source of livelihoods, with 70% of its rural households still dependent primarily on agriculture for their livelihood. India is the world's largest producer of milk, pulses, and spices, and has the world's largest cattle herd (buffaloes), as well as the largest area under wheat, rice and cotton. It is the second largest producer of rice, wheat, cotton, sugarcane, farmed fish, sheep & goat meat, fruit, vegetables and tea. The agriculture sector in India holds the record for the second-largest agricultural land in the world, generating employment for about half of the country's population. Food grain production in India touched around 330 Mt in 2022-23.

Figure 4. *Possible actors and their relationships in agri-food system to be addressed in CE.*



5.1. Agri-residues and food by-products

The agri-food sector generates many agri-residues, rich in valuable organic matter and moisture. India produces around 350 Mt of agri-residues annually. Around 3.72 to 15.05% of the agricultural production, except milk, is lost (NABCONS, 2022) in the production-to-retail chain, while there is a huge amount of waste yearly. It is estimated that one-third of all food produced globally is wasted or spoiled before it is eaten. Food waste in India is not just a national issue; it also affects the planet on a large scale, as food is a universal commodity and is not just restricted to people of a particular country. Food waste is present in all segments of food production. According to the European Agency for Environmental Protection, the main source of food waste are households (42%), followed by food processing and production plants (39%), hotels and restaurants (14%) and, finally, wholesale and retail stores – grocery shops, supermarkets and megamarkets (5%). Though there may be variations in data, this waste leads to massive emissions.

The environmental hazards associated with the waste are also immense, resulting in unnecessary carbon emissions that could have a devastating impact. Food production, distribution and storage use a lot of natural resources. At the same time, food waste contributes to climate change (food waste generates around 8% of the total amount of GHG emissions by itself). This is why the issue of sustainable food waste management is equally important from the social, environmental and economic perspectives.

Agricultural and food wastes possess a huge potential to be exploited in terms of recovering nutrients, compounds, and materials for different purposes (nutraceutical, functional foods, energy production, packaging materials). However, proper circular business models need to be established to close material loops and switch to a circular model.

5.2. Prevention of food waste generation

Reducing food loss and waste, primarily through prevention, has enormous potential for ensuring sustainable food and nutrition security, reducing greenhouse gas emissions, and lessening environmental impacts through improved resource use efficiency. Food waste can be greatly reduced by implementing efficient supply-chain practices such as cold storage facilities and better inventory management.

Rethinking the current production and consumption models and transforming waste into added-value products need to be based on new technologies, processes, services, and entrepreneurial systems that will shape the future of the global economy and society. From this perspective, the circular economy (CE) represents a game changer for the agri-food sector.

5.3. Secondary agriculture as the strategy of residue management and circular bio-economy

The committee on Doubling Farmers' Income of the Government of India highlighted the issue of food waste and food loss and recommended secondary agriculture. Secondary Agriculture has different avenues, and one of those is around wastes and crop residue utilization, establishing circular economies. Secondary Agriculture is a productive activity at the enterprise level that uses raw materials as the primary product and by-products of agriculture and other biological resources available locally in its rural agrarian neighborhood.

Among several initiatives, the Government of India has launched the 'waste to wealth' mission to identify, develop, and deploy technologies to treat waste to generate energy, recycle materials, and extract resources of value. The mission is working to identify and support the development of new technologies that promise to create a clean and green environment. The mission will also help to create circular economic models that are financially viable for waste management to streamline waste handling in the country. Value addition to the input (for example, vermicomposting) or output (village level cottage enterprises like pickle, jam, jellies, etc.) is an excellent example of utilizing locally available resources and preventing losses and waste. Similarly, alternative enterprises like sericulture, apiculture, bamboo cultivation, kitchen gardening, agro-tourism and similar enterprises do not compete for the resources on the farm and thus contribute green-positively to the income and employment generation.

Utilizing crop residues and wastes from primary agriculture, on the other hand, brings down waste in the local area and further adds to the income and employment creation. This, in turn, generates a circular economy wherein the local resources are utilized, wastes and losses are minimized, emissions are reduced, and a 'green economy' is established. In recent times, when there are limited resources, it is crucial to utilize them productively and effectively to promote sustainable and competitive value chains.

6. Roadmap for Circular Economy in Agriculture during *Amrit Kaal*

6.1. Cotton and other natural fibres

Table 2. The roadmap for the implementation of cotton circular economy and other natural fibres during processing, use and disposal.

Manufacture of textile products	Distribution & retail	Reuse, repair and Recycle	Waste management
⊙ Use State of the Art technology for processing with better monitoring of the process. ⊙ Avoid blending with other synthetic fibres ⊙ Design the product for durability, recycling and repair (circular design)	⊙ Eco-labelling of the products ⊙ Introduce price for environment externalities ⊙ Move away from fast fashion ⊙ Circular cloths should be made attractive and cheaper ⊙ Offer services for repair, buy-back to enable ease of recycling	⊙ Second hand sales ⊙ Reuse and upcycling ⊙ Fashion leasing / renting ⊙ Improve the recyclability of the fibre ⊙ Collection point and better sorting technology to foster efficient and economic recycling	⊙ Reduce the incineration and landfill ⊙ Recovering residual waste for low quality application

Manufacture of textile products	Distribution & retail	Reuse, repair and Recycle	Waste management
⊙ Adopt a closed loop production system to recover and reuse water and ensure chemical recovery ⊙ Provision for use of recycled yarn/fibre in production process ⊙ Traceability in the value chain	⊙ Education and awareness to customers on use of circular cotton textiles and other natural fibre products	⊙ Energy efficient process in recycling ⊙ Avoid downcycling	

6.1.1. Actions needed by research institutions

- Development of resource conservation technologies in processing
- Development of durable and recyclable products without affecting usability
- Technology for the upcycling of textile waste through value creation
- Work in collaboration with industry to scale up the developed technologies
- Develop the traceability solution in the cotton value chain
- Promote the technology for the use of biomass as a renewable fuel of the future

6.1.2. Actions needed by the industry:

- Use good quality materials and recycled materials
- Provide information to consumers
- Adopt circular design and timeless pieces (basics, never out of stock)
- Local production and Take-back schemes

6.1.3. Action needed by the government:

- Policy support to promote the use of recycled fibres
- Legislation on transparency, chemicals of concern, etc.

- Binding product norms to assure quality
- Internalization of environmental and social costs, e.g. carbon pricing
- Legislation on extended producer responsibility
- Environmental labelling
- Ban on landfill or waste exports

6.2. Road map for the generic model of crop-based and animal-based circular economy

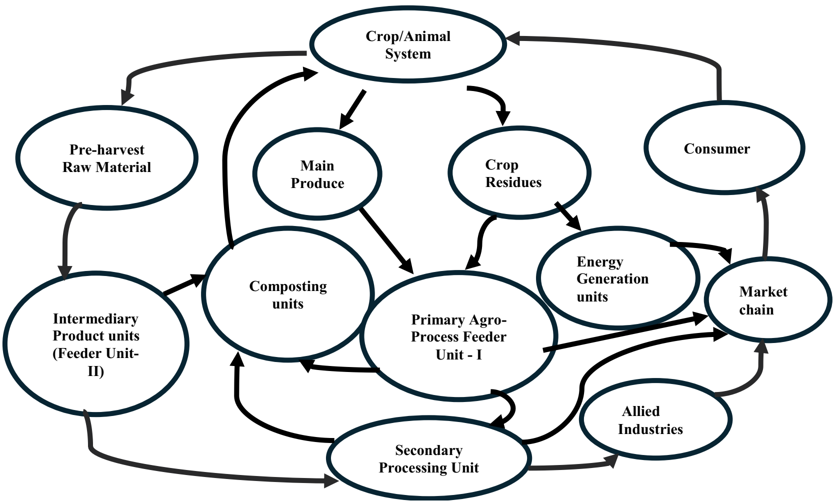
All food processing industries solely depend on agricultural and livestock production. The sector supplies raw materials for several industries, e.g., linseed oil for the paint industry, guar gum for the petroleum industry, starch for the textile industry, bioactive extracts for the pharmaceutical industry, etc. The crop residues were the main fuel source in rural areas till the recent past. However, with increased use of clean fuel for cooking and other applications, a huge surplus amount is posing handling and disposal problems. This resource can effectively be used as a renewable energy source and feedstock for extracting high-value compounds for the pharma sector.

Economy of crop/animal production system: Crop residues and processing by-products, now in surplus, pose serious environmental and health concerns because of their huge volume, low value, handling, and transportation costs. Therefore, exploitation of crop residues and processing by-products is the main challenge in the present economy model, which has to be addressed as a priority.

Crop and animal production wastes can be categorized as : (i) Pre-harvest waste, which is generated during production and being used mainly as compost, e.g. pre-mature horticultural crops droppings, pruning wastes, and animal/poultry excreta; (ii) Harvesting waste, which is generated at the time of harvesting crop/slaughtering animals/catching fish in huge quantity for a short duration, e.g. crop residues, rotten/damaged horticultural produce, animal offals, feathers, blood, uneconomical fish; (iii) Processing waste, which is generated during value addition and mainly used as animal feed or landfill, e.g. rejections of processing lines, peel & seed of horticultural produce, bran, husk, brokens and powder, effluent water, bones, skin and fatty tissues; and (iv) Food waste, which arises from not consuming the processed/prepared food within the stipulated safe life period or throwing away, e.g. surplus food in social events, food products not consumed within the safe period, spoilage due to technical failures, etc.

There is an urgent need to develop a circularity approach, a package of practices for eliminating waste and pollution by efficiently converting it into useful products, proper post-production management (handling, storage, and transportation), reducing the bulk at waste production sites, and augmenting the regeneration of the natural system. Figure 5 shows the components that form the basis for implementing the circular economy approach for crop-based/livestock-based agriculture, and is discussed subsequently.

Figure 5. *Components of circular economy approach for crop-based/livestock-based agriculture*



6.2.1. Creation and development of the agricultural input supply and guidance network

- **Partners:** Farmers group, seed companies, compost/fertilizer suppliers, pesticide suppliers, farm implement manufacturers, local mechanics, scientific & technical guiding group, input alert AI-based system developer, quality control team, soil health monitoring team.
- **Responsibility:** Farm operations time management based on demand forecast, suggesting crops to be cultivated in each season, inputs availability and pricing information and alternatives guidance, quality of inputs and their application timeliness, crop health monitoring through GIS, early warning to the farmers for pest/disease attacks &

natural calamities, ensure minor repair of instruments, training to the farmers, harvesting time decisions linked with processing facility requirements.

6.2.2. Market-linked dynamic decision making and market prediction system

Partners: Service providers for AI/blockchain/IoT-enabled apps, scientific and technical teams, local retailers, wholesalers of distant markets, and food product exporters, including Government Agencies.

- **Responsibility:** Demand and supply forecasting of identified crops and products, fixed demand forecast for distant market allied industries, daily/weekly local market demand prediction, export demand, quality requirements for customers, instantaneous monitoring and reporting of product and residue quality at different points of the market chain.

6.2.3. Procurement and collection of raw produce

- **Partners:** Farmers group, unskilled labor for harvesting (to be created from a group of farmers only), harvesting machines service providers, quality control team of skilled farmers on a rotation basis, local transport service providers (to be created from the farmers group), packaging material suppliers, and technical team to decide the locations of collection.

- **Responsibility:** Identification of fields and time for harvesting, movement plan of workers and vehicles, ensuring procurement of raw produce as per the requirement of processing unit with buffer inventory management, deciding maturity, proper harvest scheduling, traceability marking, collection guidelines, segregation of poor quality material to determine the price(not for sorting/grading or rejection), deciding the price of raw produce on the basis of quality, sampling after arrival in the processing unit, traceability record, maintenance of packaging materials, ensuring the management of reusable packaging material (crates, bags, etc.).

6.2.4. Procurement and collection of crop residues

- **Partners:** Farmers group, unskilled labor for residue collection, on-site drying and/or densification machine service provider, local agro-processing centers group with size reduction/compaction facility, local transport service providers, packaging material suppliers, technical team to decide the delivery points for crop residues.

- **Responsibility:** Synchronization with main raw produce collection team, movement plan of workers and vehicles, densification of crop residue in the field (if required), identification of size reduction/ compaction centers, inventory management, sampling after arrival in the processing unit, traceability record (if any), packaging of compacted materials, storage protocols for compacted material, arrangement of transport of primarily processed crop residues.

6.2.5. Feeder Unit-I: creation of agro-processing centers with refinement facility of crop residues (backward-linked feeder units for central processing and value-added unit)

- **Partners:** Aggregators, local agro-processing units, machinery suppliers, repair mechanics, central processing unit management team, farmers, local transport service providers (to be created from the farmers group), quality control team.

- **Facilities to be created/added:** Field dryers, compaction machines, size reduction machines, crop-residue storage area, compacted material storage shed, and composting pits (if needed). This unit will serve a 1-2 km radius and should be a maximum of 50 km away from the Central Processing Unit.

- **Responsibility:** Synchronization with a central unit, ensured processing of crop residue, densification of crop residue, packaging of compacted materials, storage protocols for compacted material, arrangement of transport of primarily processed crop residues, sale/ distribution of the compost (if available).

6.2.6. Feeder Unit-II: strengthening of agro-processing facilities for intermediary products production (backwards-linked feeder unit-ii for central processing and value-added unit)

- **Partners:** Aggregators, local agro-processing units, machinery suppliers, repair mechanics, central processing unit management team, refer transport service providers (to be managed from the central processing unit), and quality control team.

- **Facilities to be created/added:** pulp extraction machines, dryers for by-products, crushers, small capacity cold storage facility (for pulp/ extract in emergency), composting pits (if needed).

- **Responsibility:** Synchronization with central unit, ensured processing of perishables along with ensured delivery to the central unit within a stipulated time, strict quality control, drying of vegetables/by-products, bulk packaging of pulp/extract/dried products, and arrangement for transport to primarily processed crop residues, sale/ distribution of the compost (if available).

6.2.7. Central Processing Unit: processing and value addition of main produce for consumers, intermediary extract for forward linked allied industries, and compost for farmers

- **Partners:** New facility to be created or Food Parks Management, machinery suppliers, repair mechanics, farmers group, procurement team, marketing teams, refer transport service providers, quality control team, export promotion agencies, allied industries, packaging material suppliers, processing & value addition team, storage team.

- **Facilities to be created/added:** Food grains processing and value addition machines (based on local market demand), a packhouse for perishables, a warehouse, cold storage, intermediary extract separation units from by-products, a dehydration unit, a quality control and packaging unit, and composting pits.

- **Responsibility:** Management of overall activities of all the subsidiary units, farmers, procurement monitoring decision and management, production of processed products for local market, decision on diversion of fresh produce for local/export market, traceability, linkage with feeder units and allied industries, marketing, liaising with export agencies and exporters/importers, quality control, retail packaging of vegetables/by-products, policy for supplying compost to the farmers, refer transport control, cold chain management, sale/ distribution of the compost (if available).

6.2.8. Renewable energy generation services

- **Partners:** New facility to be created, machinery suppliers, repair mechanics, procurement team, logistics, storage team, Feeder Unit-I, Central Processing Unit, energy procurement agencies.

- **Facilities to be created/added:** bio-conversion and/or Bio-thermal conversion units equipped with raw material refinement and storage systems, an energy/ fuel distribution facility, and composting pits.

- **Responsibility:** Collection of compostable/ combustible crop/ agro-processing residues with sufficient energy value, ensuring regular supply and storage of raw material, sale/ distribution of the generated energy/ fuel, residue (to appropriate industry) and compost (if available).

6.2.9. Allied Industries: pharmaceuticals, animal feed, beverages

- **Partners:** Health and pharma companies, marketing team, refer transport service providers, quality control team, packaging material suppliers, storage team.
- **Responsibility:** Strict quality control with efficient storage management, ensured supply monitoring and management, exploring new avenues for allied industries, marketing, liaising with export agencies and exporters/importers, bulk packaging of vegetables/by-products, policy for supplying compost to the farmers, referring to transport control, cold chain management.

6.2.10. Allied services: laboratory, finance and market

- **Partners:** R&D organizations, private laboratories, financing institutions, and consultants (technical, logistic, finance, export, and marketing).
- **Responsibility:** Quality certification, guidance on quality norms and requirements, training to on-site personnels, preparation of DPRs, ensuring compliance of national and international quality/ hygiene/ safety norms, guidance about different schemes of financial assistance, developing new processes and products and improving production efficiency (high-recovery, better refinement, lower carbon and water footprint).

6.3. Village, panchayat, block, and district-level economic Zone

To implement the concept and roadmap of Circular Agricultural Economy, a boundary has to be defined to make them fulfil all needs and desires of living beings from within the boundary and additional unfulfilled items may be procured from outside in lieu of surpluses generated/ manufactured within the boundary and sold outside the boundary, that may be village, block, district, states or whole country. As this economic zone may be of any scale but dependent on resources generated at the village level, it may be called the Village Economy Zone (VCZ) or the Bi-Refinery Level (BRL). Each BRL may have the following, but not limited to, centers:

- Food grain, oilseeds & pulses processing
- Fruits & vegetables processing
- Milk & milk products
- Meat, fish and poultry processing
- Sugarcane/jaggery processing and value addition
- Feed, fodder and fibre processing
- Energy production units
- Local artisan/arts & craft center
- Product quality evaluation laboratory
- Marketing and at least one IT hub

The approach will not only generate huge employment opportunities at the rural level but shall also reduce product/produce movements and their carbon footprints presently incurred in transportation and marketing, and minimize labor migration.

7. Epilogue

Circular agricultural economy advances will not only improve the resilience of urban and agricultural economies in the face of turbulent change, but also will deliver benefits, including climate mitigation, food and water security, enhanced biodiversity, job creation, and empowerment of underprivileged communities. Based on circular economy principles, urban and agricultural wastes can be repurposed as industrial resources. Various proven methods and technologies are available, ranging from centralized waste collection and processing to decentralized applications that could function at a neighborhood or individual household scale. Innovations in design and communication are necessary to induce behavioral change, ranging from trash recycling to using toilets rather than open defecation. Customized strategies are needed due to the vast differences between rural villagers and urban populations. In order to advance toward a circular economy, changes in policy are needed to stimulate technological innovation and waste management improvements.

A variety of instruments are available to the government to accelerate the adoption of the circular economy concept. These include regulatory requirements, market-based incentives such as subsidies, taxes, or cap and trade schemes, payments for enhancing essential ecosystem services such as re-carbonization of soil, and information campaigns to encourage voluntary initiatives. While aspects of circular economy principles can be found in scattered provisions and regulations, a coherent focus and systematic approach would be needed, including integration of circular economy ideas into existing government initiatives. The following recommendations can guide Indian policymakers at the national, state and local/city levels in supporting the transition to a circular economy:

- **Provide incentives for businesses** that lead a circular economic path towards development. Tax incentives may be given to stimulate the use of greener and cleaner product and process technologies.
- **Foster innovation** by design in the area of circular economy and help small and medium-scale enterprises reach scale on efficient technologies.
- **Create platforms for multi-stakeholder collaboration** by connecting different actors—businesses, government, the informal sector, and research institutions—to consider product and material flows from the design stage to collection and return for reuse and recycling.
- **Design Standards** should include resource efficiency and the use of secondary raw materials. Product eco-labelling schemes should further help disclose recycled content and other environmental benefits.
- **Support circular models through public procurement** that would boost promising and scalable circular business models and increase their adoption.
- **Introduce circular economy principles** into the formal and informal education system to inspire the younger generation. This would enable the young generation to think, innovate, and design products and systems suitable for a circular economy. This would empower learners at all stages with the right skills and mindsets to become active shapers of the future economy.
- **Raise consumer awareness** about the benefits of the circular economy through campaigns in print, broadcast, and social media.

A comprehensive approach to the circular economy in agriculture will significantly contribute to India's development agenda by increasing the incomes of farmers and industry, generating employment opportunities in rural and urban areas, reducing GHG emissions, and making India a developed nation by 2047.

8. References

Accenture. (2015). The circular economy could unlock $4.5 trillion of economic growth, finds new book by Accenture. https://newsroom.accenture.com/news/2015/the-circular-economy-could-unlock-4-5-trillion-of-economic-growth-finds-new-book-by-accenture

Cimren, E., Fiksel, J., Posner, M. E., & Sikdar, K. (2010). Material flow optimization in by-product synergy networks. Journal of Industrial Ecology, 15(2), 315–332.

Fiksel, J. (2011). Design for environment (2nd ed.). McGraw-Hill.

Fiksel, J., Sanjay, P., & Raman, K. (2021). Steps toward a resilient circular economy in India. Clean Technologies and Environmental Policy, 23, 203–218.

NABCONS. (2022). Study to determine post-harvest losses of agri produces in India.

World Economic Forum (WEF). (2013). Towards the circular economy: Accelerating the scale-up across global supply chains. World Economic Forum. https://www.weforum.org/reports/towards-the-circular-economy

10 Water-Energy-Food-Ecosystem Nexus

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1. Context

During the last 50 years, the Food and Agriculture System, which was undergoing gradual evolution, has undergone transformative changes. Industrialization of Food and Agriculture System (FAS) from 1960 onward, which tremendously increased the food supply, has created dramatic environmental consequences, accelerated climate change, biodiversity loss, land degradation, desiccation and degradation of water resources. Rejuvenating health and further enhancing the carrying capacity of the degraded Natural production system, particularly land, water (surface, ground and sea) and atmosphere, without compromising the food security of the growing population, remains a broad issue to be addressed (Happy people and a Healthy ecosystem). To achieve the cherished goal of 'Happy people and Healthy Ecosystem', it is imperative that a road map detailing the action plan is evolved and implemented.

The concept of the water-energy-food-ecosystem (WEFE) linkages has caused a rapidly developing impact on the sustainability debate as the world community attempts to handle the mounting problem of resource management, without compromising the security of food and the environment. This is because the WEFE nexus approach proposes integration and interdependence across various sectors to ensure resource security in the climate crisis, resource scarcity, and increasing and competing demands for water, energy, and food. According to (Muller 2015), "nexus thinking" is an alternative paradigm that addresses connected problems by

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considering sets of interrelated sectors and treating the complexity of related issues holistically. With consideration for resource allocation trade-offs and synergies, the Water-Energy-Food (WEF) Nexus outlines the intersection of the problems pertaining to water availability (quantity and quality), energy production, and food production. The WEF nexus method emphasizes concurrent analysis of cross-sectoral issues and engagement with different sectors, while the IWRM framework concentrates on a complete approach from a mono-sectoral (water sector) perspective.

The security of food, energy, water and the environment is closely related. In short, water is required for producing energy, and energy is required for pumping, purifying, and distributing water. Production and processing of agricultural commodities require energy inputs in tillage, irrigation, fertilizers, harvesting, and transportation. The developments in the three systems affect the local as well as global environment. The deepening of the relationships that currently exist between the three systems is facilitated by growing economies, population, and climate change. A novel strategy that is more focused on the connections and interdependencies between the food, energy, and water sectors, as well as the effects of trade, investment, and climate policy, is needed to alleviate the current levels of insecurity in access to essential services.

1.1. Questions that the WEFE nexus approach tries to answer

It is emerging as an instrument for development planning and holds promise for India, where five transitions (urbanization, nutrition, energy, agriculture, and climate) are simultaneously impacting WEFE security. The WEF Nexus approach directly addresses three Sustainable Development Goals (SDGs): 2 (No Hunger), 6 (Clean Water and Sanitation), and 7 (Renewable Energy), but indirectly impacts all 17 goals.

2. Status of Water, Energy, Food and Environment Security in India: Challenges and Opportunities

India is undergoing rapid transitions in demographic patterns, income level, food consumption, agricultural production systems, energy use, and climatic changes. Broadly, these transitions are characterized by rising level of urbanization, increasing income and purchasing power of the households, shift in consumption from staple (calorie rich) to high value (protein rich) food products, shift from subsistence to commercial farming, shift from fossil fuels to renewable energy sources, and increasing frequency and intensity of climatic aberrations. As India envisions becoming a developed country by 2047, these transitions are expected to accelerate over time (Table 1). This requires alternative modes of developmental planning and implementation to address the water, energy, and food security-related emerging issues. As food security is intricately linked with water and energy, the Water-Energy-Food (WEF) nexus approach has gained prominence in recent scientific and political discussions. WEF nexus approach recognises inter-connections among these sub-sectors. It applies multi-disciplinary and inter-sectoral measures to optimize the use of natural resources (e.g., land and water) within the planetary boundaries and address the emerging challenges of the sustainable food system. However, despite occupying a prominent

Table 1. Transitions impacting Water-Energy-Food (WEF) security in India.

Transition from	2020	2047
Demographic transition:		
Population (million)*	1390	1654
Urbanization (%)*	34.9	50.9
Economic transition:		
GDP (USD/capita/Annum)#	1941	26,974
Food transition:		
Food consumption (grams/capita/day)$	1000	1530
Share of cereals in food consumption (%)$	36	24
Energy transition:		
Per capita primary energy consumption (kWh)^	7017@	12547-13477
Installed capacity of non-fossil fuels (%)^	43.7@	85-90
Agricultural transition:		
Shift from small scale subsistence farming to commercial operations**	85% farms ≤ 2 ha	Farm size expected to increase due to urbanization and shift to industry and service sectors
Climate transition:		
Increasing temperature, variable rainfall, greater crop water demand**	It is impacting. No estimates	2°C rise, rise in water demand by 10-15%.

Source: *https://www.pib.gov.in/PressReleasePage.aspx?PRID=1705772*

*United Nations (2022), #PWC (2024), $NITI Aayog (2024), ^Ram and Mothkoor (2022, @value for the year 2022, **Tyagi (2020) place in scientific deliberations, different sectors of the WEF are managed independently to each other in the country.

Simpson *et al*. (2022) have developed a composite WEF nexus index (CWEFI) based on 21 indicators representing water, energy and food sectors to assess and compare their status across different countries (Table 2).

Table 2. Indicators of the composite Water-Energy-Food (WEF) nexus index and their values for India in 2023.

Water		Energy		Food	
Indicator	**Value**	**Indicator**	**Value**	**Indicator**	**Value**
The percentage of people using at least basic drinking water services (%)	90.5	Access to electricity (% of population).	99.6	Prevalence of undernourishment (%)	16.3
The percentage of people using at least basic sanitation services (%)	45.9	Renewable energy consumption (% of total final energy consumption).	35.8	Percentage of children under 5 years of age affected by wasting (%)	18.7
Degree of IWRM implementation (1-100)	45.0	Renewable electricity output (% of total electricity output).	15.3	Percentage of children under 5 years of age who are stunted (%)	31.7
Annual freshwater withdrawals, total (% of internal resources)	44.8	CO_2 emissions (metric tons per capita).	1.6	Prevalence of obesity in the adult population (18 years and older)	3.9
Renewable internal freshwater resources per capita (m^3).	1,035.5	Electric power consumption (kWh/capita).	797.4	Average protein supply (grams/capita/day).	65.7
Environmental flow requirements (10^6 m^3/annum).	937.1	Energy imports, net (% of energy use)	34.3	Cereal yield (kg/hectare)	3,478.8
Average precipitation in depth (mm/annum).	1,083			Average Dietary Energy Supply Adequacy (ADESA) (%)	110
				Average value of food production (I$/capita)	61

Source: *Simpson et al (2022). https://wefnexusindex.org/*

India's WEFI for 2023 was 51.83%, with its three pillars -the food index (FI), the energy index (EI), and the water index (WI) showing correspondingly low levels of integrated resource planning at 55.5, 54, and 46%. Of the 165 assessed countries, India is ranked at the 115th position based on CWEFI for the year 2023. This indicates that India lags far behind other countries regarding WEF security. CWEFI value for India is estimated at 51.9 as compared to the highest value of 81.2 for Iceland and the lowest value of 34.8 for the Central African Republic for the year 2023.

2.1. Water-energy-food (WEF) security

2.1.1. Food security

Food security exists when all people have physical, social, and economic access to enough safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. According to the Food and Agriculture Organization (FAO), food security has four dimensions: availability, physical and economic access to food, food utilization, and stability.

Availability dimension explores the adequacy of food products for meeting the demand in a given geographical location. India has made significant progress in producing food for the rising population. Technological advancements, enabling policies and institutions, have transformed India from a food-deficient economy to one that is not only food-sufficient but also a net exporter of agricultural commodities at the aggregate level. During the last seven decades, the per capita food production[7] has increased 2.36 times, from 772 grams/day in 1950-51 to 1826 grams/day in 2020-21. Higher growth in food production than in the population shows an improving status of the nation's food security. India currently produces sufficient food to meet domestic demand, except for few commodities such as edible oils and pulses.

By 2047, when India envisages becoming a developed country, the population is expected to surpass 1.6 billion, and about half of it will live in urban areas. Further, the consumption basket of Indian households is poised to diversify towards high-value food commodities such as fruits, vegetables, milk, non-vegetarian items, etc. and the use of food commodities as feed, fibre, fuel, and in nutraceutical and pharmaceutical industries is expected to increase significantly. Thus, food demand and diversity in food consumption patterns will likely increase significantly.

[7] Including cereals, pulses, edible oils, sugar, fruits, vegetables, milk, meat, fish and eggs

Recently, a Working Group of NITI Aayog has projected food demand to grow at annual growth rate of 2.44 to 3.07% between 2019-20 to 2047-48 with higher growth in the demand of high value food commodities such as fruits, vegetables, milk, non-vegetarian items as compared to the staple foods such as rice, wheat, etc. (NITI Aayog, 2024). It is therefore necessary to maintain at least 3% growth in food production and accelerate diversification of the food production basket towards nutritionally rich and high-value food commodities. It is projected that domestic production will be sufficient to meet the domestic demand for most commodities in 2047.

Domestic production's adequacy to meet present and future food demand is a necessary but not sufficient condition for ensuring food security. This is indicated by the fact that despite adequate production, India performs poorly regarding nutritional outcomes. According to the National Family Health Survey 2019-20, about 32% of the children under five years of age are underweight, 35% are stunted, and 19% are wasted. These evidences underscore the access (physical and economic) and utilization dimensions of food security. Controlling food prices within affordable limits and effectively covering poor households under the food safety programs to improve economic access to food is paramount in a country like India. Similarly, absorption of nutrients from the food intake within the human body (utilization) depends largely on access to sanitary conditions, clean water, an improved sewage system, etc.

It is to be noted that the possibility of bringing more land under cultivation is limited due to intense inter-sectoral competition. Rather, agricultural land has declined by about 5 Mha between 1991-92 and 2019-20. Therefore, incremental food production should come from improving productivity and intensifying existing agricultural land through multiple cropping. Although India is one of the top producers of several food commodities in the world, it lags behind in productivity (NITI Aayog, 2024). There exists enormous potential to improve productivity by raising the frontier yield levels through technological innovations and bridging existing yield gaps through technological dissemination, and improving the efficiency of the resources used in food production. Further, food production system is expected to come under the confluence of various biotic and abiotic stresses, which need to be addressed by improving agriculture's resilience and adaptive capacity. Given the certainty of climate change, improving stability in the supply of food commodities has emerged as a significant challenge for sustaining food security in the nation.

2.1.2. Water security

India supports about 16% of the world population with only 4% of fresh water. As water is a critical input for food production, food security is directly linked to water security. The usable water resources of the country have been assessed at 1126 billion cubic meters (BCM), of which 690 BCM is from surface water and 436 BCM from groundwater sources. Most of the usable water in India is available during a short span of 3-4 months, i.e. June-September, and wide spatial variability exists. It is to be noted that the country has a surface storage capacity of 305 BCM, which is only 15% of the average annual flow (1999 BCM). Therefore, controlling run-off and conserving water through various means of storage and on-farm interventions are necessary for augmenting the availability of resources for multiple purposes. Judicious and efficient use of water is an essential supplement to its conservation. With the rising human population, per capita availability in India is declining, from 5178 m^3/year in 1951 to 1486 m^3/year in 2021. The country's water demand is projected to surpass usable availability by 2051 (Table 3). Managing such situations warrants the implementation of effective supply augmentation and efficient demand management measures in water management.

Table 3. Key indicators of water security in India.

Indicator	2021	2051
Per capita water potential (m^3/person/year)	1486	1228
Per capita utilizable water availability (m^3/person/year)	835	690
Per capita water requirement (m^3/person/year)	813	889

Source: *Central Water Commission*

Among all sectors, irrigation is the predominant user of water resources, consuming about 85% of the total water demand. With the rising level and changing composition of food demand towards water-intensive food commodities, water demand for irrigation is projected to increase in future. But the share of irrigation in total water demand is expected to decline due to inter-sectoral competition. According to Central Water Commission (2021), the share of irrigation in total water demand will reduce from 78.2-84.6% in 2010 to 64.5-74.0% in 2051. This implies agriculture should produce more food using less water. In other words, water use efficiency in irrigation has to be significantly enhanced to sustain the country's food security. Improvement in irrigation efficiency would substantially contribute to overall water conservation, given its large share in total water demand.

Over the years, India has witnessed a massive improvement in irrigation infrastructure, catalyzing food security. Various studies have established direct productivity and income-improving impacts, and indirect poverty-reducing implications of the improvement in irrigation in India (Saleth 1996; Vaidyanathan 1999; Hasnip *et al*. 2001; Bhattarai *et al*. 2002; Saleth *et al*. 2003; Narayanamoorthy and Bhattarai 2004; Narayanamoorthy 2007; Srivastava *et al*., 2014). However, large positive impacts of the irrigation development coexist with negative outcomes. Many studies have pointed out that irrigation development in the country is unsustainable, and its benefits are not equally distributed across regions and people. The following challenges have emerged in India's irrigation sector, which need immediate attention:

- About 81% of the total Ultimate Irrigation Potential (UIP) has been created till the XI Five-Year Plan, which limits further expansion in irrigation infrastructure on a large scale. Further, a gap of about 25 Mha or 23% exists between IPC and IPU. Modernisation of the canal irrigation system and improving water use efficiency through adopting technologies, such as micro-irrigation, can bring a substantial area under assured irrigation.

- Groundwater irrigation has emerged as a major source of agricultural development in India. However, groundwater is unsustainably used for irrigation, leading to over-exploitation in several countries. About 25% of the total assessment units (blocks/mandals/taluka) have been categorized as over-exploited/critical/semi-critical, where groundwater is depleting at an alarming rate (CGWB, 2023). Most of these areas are located in the northwestern and southern parts of the country. On the other hand, groundwater resources are underutilized in most of eastern India, primarily due to poor economic access of the farmers to groundwater irrigation. There exist dual challenges in reversing over-exploitation of groundwater in some areas and promoting its sustainable use in others.

- The availability of free or subsidized electricity for groundwater irrigation is one of the major reasons for overusing scarce groundwater resources. As water levels deplete, the requirement for energy to extract groundwater increases significantly, raising both irrigation costs and energy-led emissions. Thus, conducive energy pricing policies play a key role in the sustainable utilization of water resources.

- The actual consumptive use, the portion that is actually used for the net evapotranspiration of crops, is only 41% at the national level. The difference between the consumptive use and actual water withdrawal indicates poor efficiency. Studies have revealed that India uses 2-3 times more water than major agricultural countries like China, Brazil and the US to produce one unit of food crop. With a 10% increase in water use efficiency in irrigation projects, an additional 14 Mha area can be brought under irrigation, which would significantly enhance the farmers' stability in production and income. Overall, there exists a potential to increase water use efficiency up to 60% from the existing level of 35-40%.

2.1.3. Energy security

India is the third-largest energy consumer in the World. On a per capita basis, energy consumption in India is almost half (7017 KWH/capita) of the world average, $1/5^{th}$ of China's and $1//10^{th}$ of the US. But as the country aspires to become a developed nation by 2047, energy demand is expected to increase 2-2.5 times for improving infrastructure and manufacturing base (NITI Aayog, 2023). India is making concerted efforts towards becoming net-zero by 2070 and energy-independent by 2047. The goal of energy independence means reducing energy imports and ensuring a reliable supply of energy at affordable prices. As about 85% of crude oil and 49% of gas requirements are met through imports, the strategy to reduce import dependency shall be to reduce the demand for such products and increase domestic production capacity. In this context, the Indian government has prioritized significantly improving installed renewable energy capacity to provide clean and affordable energy. Some of India's energy security indicators are presented in Table 4.

Agriculture constitutes only a 5.65% share of total energy demand, which is expected to decline to 3.79% by 2047 due to higher growth in the demand from non-agriculture sectors. However, the absolute demand for energy in agriculture is expected to increase 2.3 times during the next 25 years. Within agriculture, a large part of the energy demand would come from the irrigation subsector. Energy is closely intertwined with most of the water management technologies, particularly groundwater irrigation, and thus plays a critical role in sustainable water management.

With 21.9 million wells and tubewells, India is one of the largest users of groundwater in the World. Successive Minor Irrigation (MI) Censuses reveal about four times increase in the number of wells to extract the groundwater for irrigation in the country.

Table 4. Indicators of energy security in India.

Indicator	2022	2047
Total energy supply (Mtoe)	857.5	2895.5
Total energy demand (Mtoe)	618.4	2199.6
Energy use in agriculture (Mtoe)	35.0	83.4
Share in total energy demand (%)	5.7	3.8
Electricity supply (TWh)	1408.9	6168.2
Electricity demand (TWh)	1314.2	2336.9
Electricity use in agriculture (TWh)	203.2	642.4
Share in total electricity demand (%)	15.5	27.5
Per capita primary energy supply (toe/person)	0.6	1.8
Per capita GHG emission (Kg CO_{2e}/person)	2.0	6.0
Energy emission intensity of GDP (kg CO_{2e}/1000 Rs.)	18.2	9.5
Energy intensity of GDP (MJ/INR)	0.2	0.1
Installed capacity of non-fossil fuels (%)	43.7	85-90

Source: *NITI Aayog (2023)*

In most of the states, electricity supply for irrigation is provided either free or at highly subsidized tariffs, which gives no incentives to the farmers to save water. Subsidized/free electricity coupled with widespread adoption of the flood irrigation method leads to injudicious and inefficient groundwater use. Agriculture sector consumed about 20% of the total electricity consumption. It constituted 66% of the total loss incurred to the DISCOMS from supply power at subsidized tariffs rather than the actual supply cost during TE 2020-21. This loss is borne by the government as a power subsidy, which has been estimated at Rs 75,017/- crore for the period TE 2020-21. Further, wide inter-state variation in power subsidy (Rs/ha NSA) exists, which indicates that the benefits of the subsidy (like improved economic access) are inequitably distributed. Rationalizing subsidies and incentivizing farmers to use the groundwater resources judiciously has become a major challenge in India.

In addition to depleting groundwater, the rising number of GEDs and energy intensity also contribute to climate change by emitting greenhouse gases (GHG). Later, climate change poses a serious threat to water security. Thus, addressing the water-energy-climate nexus has become essential for developing a sustainable food system. Groundwater irrigation can be made more energy and carbon-efficient by implementing measures such as improving pump efficiency, adopting micro-irrigation, rationing electricity supply, improving on-farm efficiency, etc. Introducing new pumps, replacing conventional pumps with highly efficient pumps and promoting solar-powered irrigation systems can substantially reduce the growing carbon emissions.

To provide economic access to irrigation and ensure energy security in the nation, the Central and State governments are promoting renewable energy sources such as solar power. The total number of solar pumps in India has increased significantly- from 11626 in 2013 to 501673 in 2022. Given the commitments to developing climate-resilient food systems and improving affordable energy sources for farmers, transitions toward renewable energy sources like solar energy are expected to accelerate. However, desirable outcomes with solar energy, such as economic access to irrigation, reduction in carbon emission, etc, may accompany some unintended consequences like the risk of over-use of groundwater. It is therefore essential to negate such risks through technological interventions and institutional innovations.

(i) Environmental concerns

One of the basic premises of the WEF nexus approach is to consider the planetary boundaries of natural resources and the environment. WEF nexus recognizes the trade-off between using water, energy and food to meet human needs and the planetary boundaries of their availability or environmental impacts. For instance, it emphasizes the need to maintain minimum environmental flow in the river basins (10-15% of the average lean season flow), to restrict groundwater extraction within the annual rechargeable limits, reduce groundwater exploitation in coastal areas to check sea water intrusion, etc.

India is placed rather low in the global environmental performance index (EPI). The major environmental issues faced by India include:

(ii) Water pollution

Water bodies suffer from contamination due to industrial waste, sewage, and agricultural runoff. Almost 70% of its surface water resources and a growing percentage of its groundwater reserves are contaminated by biological and toxic elements. Tests indicate that the biological contamination of surface water sources due to untreated or partially treated sewage exceeds permissible limits at many locations. Similarly, overexploitation of groundwater, besides other human activities.

Groundwater depletion: Groundwater supplies are rapidly depleting due to excessive withdrawals for agricultural, industrial, and home use, and the quality of the water is declining as a result.

Sea water ingress in coastal areas: The land and coastal aquifers are becoming more salinized as a result of sea level rise and excessive aquifer extraction

Land degradation: An estimated 146.82 Mha of land is affected by complicated issues such as alkalinity/salinity and soil acidity caused by waterlogging and different forms of land degradation caused by wind and water erosion. Soil degradation impacts agricultural production and ecosystem health.

Biodiversity Loss: Habitat destruction and fragmentation threaten India's rich biodiversity

2.2 Role of WEF nexus approach

[8]As India begins chasing the vision of becoming a developed nation by 2047, ongoing transitions in different sectors are expected to accelerate with definite implications on food, water and energy. The emerging challenges would further be aggravated by the certainty of climate change. The WEF nexus approach identifies interdependencies among the sectors and provides feasible solutions, particularly when emerging challenges in different sectors are intertwined. Some instances where the WEF nexus approach fits well are energy regulation and pricing for reducing groundwater over-exploitation, promoting micro-irrigation for improving water use efficiency as well as crop productivity, improving economic access to irrigation through affordable and clean energy sources such as solar energy, coupling micro-irrigation for reducing risk of solar-power on over-use of water, etc. Thus, the WEF nexus approach, if applied, may be helpful to identify options to manage water resources to meet food security and to achieve energy security.

3. Research Themes on WEFE Security Nexus

WEFE Security covers a large area, encompassing most things on land, sea, and atmosphere. Given the need to utilize scarce resources as effectively as

[8] "The WEF nexus is essential for developing a region, avoiding risking the security of one resource over another, and looking for alternatives that can help increase the response or efficiency of the region" (Medeiros *et al*., 2020).

possible, it is crucial to identify prospective issues and prioritize research-for-development activities. The following are some of the priority areas on the WEFE nexus.

3.1. Sustainable groundwater development and use (2025-30)

In India, groundwater is the major source of irrigation and drinking water. The sustainability of this precious resource is under threat due to overexploitation, quality degradation due to pollution by municipal and industrial waste waters, and seawater intrusion in coastal aquifers. The Government of India prioritizes enhancing and protecting this renewable natural resource. The development and use of groundwater have a strong linkage with energy use and agricultural production:

***Projected output*:** Optimized plan for sustainable development and use of groundwater, with stabilized water level, reduced energy consumption and minimized GHG emissions

Some of the important research issues under this theme are listed here.

- Mapping Policy for solar irrigation across the country's Water–Energy–Food (WEF) Nexus.
- Large-scale introduction of solar pumps and groundwater micro-irrigation and its implications on groundwater sustainability.
- Minimum support price (MSP) and electricity subsidy, and crop diversification to reduce groundwater use.
- The prevention of sea water intrusion in coastal areas and the augmenting of surface water supply through surface and subsurface dykes on rivers in coastal zones and their implications.

3.2. Wastewater treatment and reuse (2025-30)

Since more and more wastewater is produced due to accelerated urbanization and economic development, there is an increase in water pollution throughout the water cycle. Unlike untreated wastewater, safely managed wastewater is a more economical and sustainable supply of nutrients, energy, water, and other recoverable resources. In an era of circular economy, wastewater management is fundamentally about augmenting the limited water supply and minimizing environmental contamination. But regardless of the supply augmenting potential, there are trade-offs in terms of the cost associated with the level of treatment and the health effects for farmers and consumers.

Expected outcomes: Quantified addition of safe water supply, with nutrients for use in irrigation, reduced pollution of fresh water, and harvest of nutrients from solid waste. It would put a circular water economy in place.

- Nexus approach and safe use of wastewater in agriculture.
- Trade-off of WEFE Nexus in wastewater treatment through Nanotechnology
- Urban water-energy-food-climate nexus in integrated wastewater and reuse systems.
- Water-energy-food security nexus-based selection of energy recovery from wastewater treatment technologies.
- Water-energy-food-climate nexus in an integrated peri-urban wastewater treatment and reuse system.

3.3. WEFE Nexus analysis of important river basins using integrated modelling (2030-40)

Expected outcomes: Some of the identified subthemes are given below.

- Generating river-basin specific primary and secondary baseline datasets on hydro-meteorological, land, crop, and water and energy use variables linked to the water-energy (WE), energy-food (EF), water-food (WF), water-energy (WE), and food-energy (FE) nexus elements.
- Assessing the existing nexus sustainability index for different river basins in India using sustainable development (SD) or life cycle assessment (LCA) modelling tools.
- Development of current data-based water, energy, food and ecosystem indices of different river basins in the country.
- Optional water development strategies for balancing the river basin's agricultural and ecological water demands.
- Optimizing the future resource allocation (trade-off) to WEFE nexus elements to achieve the maximum sustainability based on future policy options, accounting for developmental scenarios in each planning unit.
- Exploring synergies in the water–food–energy nexus by using an integrated hydro-economic optimization modelling approach.

3.4. Bioenergy (2025-30)

Bioenergy is energy produced by biological materials, such as agricultural wastes and specially grown energy crops like sugarcane. It substitutes fossil fuels, lowers carbon footprints, and lessens reliance on non-renewable resources like oil. India is committed to reducing its fossil fuel consumption to meet its net-zero carbon target. But it's crucial to evaluate how bioenergy production affects ecosystems, food security, and water availability.

***Outputs*:** Quantification of trade–offs between energy and water. The results would be the basis for planning land and water use for energy and food. Given below are some of the identified subthemes.

- Effect of bioenergy expansion: Food, energy, and environment.
- Accounting for the water impacts of ethanol production from sugarcane in Maharashtra.
- Economic potential of bioenergy for climate change mitigation with special attention on water and food security.

3.5. Crop diversification (2025-30)

Water use, energy allocation, ecosystem services, and the profitability of the agricultural operation are just a few ways that crop diversification—growing a range of crops—affects the WEFE nexus. Although there are advantages, the WEFE nexus confronts the following obstacles when implementing agricultural diversification: i) water, energy, and agriculture policy integration frequently ignores the linked effects of these sectors; ii) overlaps and trade-offs arise from the possibility that some programs may inadvertently overlap or adversely affect other sectors. Quantifying trade-offs requires an integrated strategy incorporating modelling using the WEFE lens.

***Expected outputs*:** Region-specific ecologically compliant cropping plan with minimum trade-offs regarding water, energy, and GHG emission footprints. Identified projects are listed below.

- Exploring optimal cropping across India based on water-energy-carbon footprints interactions.
- Growing food demand and the sustainable intensification of agriculture in India: Assessment.
- Water and energy-smart food under climate change across the country and its implications for resource use, the economy, and the environment.
- Reconciling resource uses: Assessment of the water-food-energy-ecosystems nexus in environmentally sensitive hot spots.

3.6. Watershed management (2030-35)

The adaptable, multidisciplinary strategy known as "integrated watershed management" (IWM) seeks to maintain ecosystem integrity and production within a watershed. It preserves and restores ecosystem services by considering soil, water, plants, and animals. IWM tactics heavily rely on technological innovations like big data, GIS, remote sensing, and multi-level social-ecological systems analysis. Nevertheless, there are trade-offs with the extent of the area that needs to be addressed, the kind of technological interventions, and downstream channel flows.

Expected output: Balanced trade-off between upstream and downstream water availability, cost-effective plan for watershed treatment.

3.7. Hydrologic and agricultural earth observations (EO) and modelling (2030-40)

Earth Observations (EO) from satellites and models have made important contributions to scientific research and decision-making. These can find applications at the nexus of water and food security.

Expected output: Data on temporal variations in water availability, information on trends in impacts of agricultural practices on the environment. Some areas of application are listed below.

- Water availability monitoring for food and water Security.
- Modelling agricultural impacts across time horizons.
- Crop Monitors for early warning

It should be noted that the timelines shown for each theme are approximations and may change after thoroughly examining the material available and identifying researchers possessing the necessary knowledge and experience to work on a particular issue.

4. Technologies and Policies for WEFE Nexus Implementation

The execution of WEFE nexus solutions is planned, designed, and implemented on the ground using suitable technologies and desired policies, which are briefly described in this chapter.

4.1. Technologies

There are several technological options that may be used to increase the resilience of food and agriculture systems. The objective criterion for selection is that the technologies should lead to improvement in soil health, reduce GHG emissions, and help maintain ecosystem services. The guiding principles for building resilience in food production systems are based on limiting the use of natural resources, adaptive allocation, transparent markets, and maintenance of environmental flows. Minimizing economic and environmental trade-offs often remains an issue in observance of these principles. The technological options to address WEFE Nexus security issues are generally grouped into the following categories.

4.1.1. Water security

- Efficient irrigation techniques: Adopting water-efficient irrigation methods, such as drip irrigation, laser land levelling, deficit irrigation scheduling, precision agriculture, etc., which help optimize water use in agriculture while maintaining crop productivity.

- Climate-resilient agriculture: Developing crop varieties and agricultural practices that can withstand climate change impacts, such as drought-resistant crops or agroforestry systems, conservation agriculture, and crop diversification.

- Water harvesting and storage: Capturing rainwater and storing it for agricultural or domestic use helps enhance water availability during dry periods.

- Ground water recharge: Augmenting ground water through artificial techniques in order to arrest ground water table decline and intrusion of sea water in coastal aquifers. Mapping of aquifers for hydraulic and quality parameters; Efficient and affordable recharge technologies; Design of skimming wells; Design of surface and sub-surface dykes for increase.

- Wastewater reuse/sea water use**:** Treatment of municipal and industrial wastewaters using newly emerging technologies like Nanotechnology to promote a circular economy and desalination of seawater.

- Nanotechnology can play a crucial role at the intersection of water, food, and energy, offering opportunities and challenges. It can enhance water treatment methods, allowing for greater reuse and safer drinking water. High-sensitivity sensors based on nanomaterials can improve water quality monitoring.

4.1.2. Energy security

- Renewable energy resources: Transitioning to renewable energy sources (such as solar, wind, hydropower, and biofuels) reduces the strain on water resources and contributes to sustainable energy production.
- Smart grids and demand-side management: Smart grids enable efficient energy distribution, while demand-side management strategies encourage consumers to use energy during off-peak hours.
- Reducing overall energy demand through the replacement of inefficient pumps with energy-efficient pumps
- Nanotechnology enables green energy generation through powerful solar cells. It also improves energy distribution and storage efficiency.

4.1.3. Food security

- Breeding higher productivity crop varieties: Development of hybrids and genetically modified crops requiring less water and applied nutrients to increase food supply.
- Nutrient fortification of crops to care for unmonitored nutrition programs and poor diet diversification.
- Disease, pest and weed control technologies to reduce crop losses.
- Reduce food loss and waste through improved value chains, handling, transport, processing, and storage technologies for demand management.
- Poverty and population growth- Improving supply and access through policies
- Buffer storage for controlling price fluctuations.
- Nanomaterials have the potential to increase food production efficiency. They can enhance safety, shelf life, and reduce costs (Malakar and Cooper,2022). But there are some potential risks.

4.1.4. Ecosystem security

- Ecosystem-Based Approaches: Protecting and restoring ecosystems (such as wetlands, forests, and watersheds) contributes to water quality, biodiversity, and overall system resilience. Technologies such as forest management, conservation farming, and river flow management help address ecosystem security.

4.1.5. Models and data

An integrated strategy that incorporates stakeholder involvement, policy analysis, and modelling is needed to address the WEFE nexus. Insights into the effects of farming practices on resource efficiency, socioeconomic outcomes, and environmental impacts can be gained by using a modelling toolkit that integrates biophysical and socioeconomic aspects related to agriculture (e.g., WaSim to simulate water use and availability, Economic modelling to assess economic impacts, and Life cycle environmental assessment -LCA to evaluate environmental impacts).

Data on system boundaries, spatial dimensions, the genesis and destiny of WEF commodities, as well as cross-sector interactions and interfaces, are critically needed. To address issues, comprehend the WEF connection, and promote sustainable resource management policies, data collection instruments are essential. Earth observations are essential for providing the data and scalability to monitor relevant indicators across space and time, as well as understanding agriculture, the hydrological cycle, and the water-food nexus (McNally *et al*., 2019).

4.1.6. Advanced technologies for monitoring and management

- Artificial Intelligence (AI) and Machine Learning (ML): These technologies can analyze large datasets from ecosystems, identify patterns, and predict potential threats or vulnerabilities.
- Internet of Things (IoT): IoT devices can collect real-time data on environmental conditions, wildlife behavior, and ecosystem health. This data helps in the early detection of disturbances.
- Data Analytics: Analyzing ecosystem data helps identify trends, anomalies, and potential risks.

4.1.7. Climate change graded incremental, trade-off and transformative technologies

The impact of the rise in greenhouse gases (GHGs) under climate change is addressed through two distinct but complementary approaches—mitigation and adaptation. In agriculture, the opportunities for adaptation, which connotes adjustment to moderate the impacts of climate change, are higher than those for mitigation. As the degree of climate change increases, the efficacy of the adaptation measures goes down, and so do the benefits, requiring a change from incremental adaptations to systems adaptations and finally transformational adaptations like the ones indicated in Table 5.

Table 5. Adaptations in relation to the degree of climate change and benefits from adaptations.

Degree of climate change	Nature of adaptation	Benefit/cost/ trade-off
Moderate	Incremental: Crop varieties, planting dates, spacing, nutrient management, canopy management, irrigation scheduling	No regret technologies
High	Systemic: Climate ready crops, precision agriculture, crop diversification, crop insurance, micro- finance and risk management, early warning systems	Income-environment trade-off-
Extreme	Transformational: Land use changes and distribution, ecosystem services, migration	High Income-environment trade-off

Source: *Based on Howden et al. (2010).*

Further, there are limits on the effectiveness of the measures arising from biophysical factors (ecological tipping points), which create absolute limits for adaptation, social limits (how much is acceptable), and economic limits (how much is affordable) (Schipper and Lisa, 2009).

4.2. Policies for implementing the WEFE nexus approach

Both science/data and public policy are necessary for WEF Nexus sustainability**.** As research methodologies for the WEF nexus continue to advance, the next step is to ensure that the suggestions are adequately incorporated into policy and decision-making. To move away from the existing conventional system to a WEFE nexus paradigm, it will be necessary to address and resolve a number of difficult problems through policy interventions at the national and state levels. Some of these challenges include developing institutional and human resource capacities for nexus-integrated strategy and execution, bridging the science-policy gap, creating suitable nexus governance and institutional structures, pricing and subsidy policies, and encouraging the private sector to lead nexus-related projects.

The water-energy-food (WEF) nexus issues in India are increasingly recognized in scientific discourses, and research has yet to gather critical mass. Further implementation on a large scale will require bridging the science–policy interface, nexus governance and institutional structures, the building of human resource capacities, and an increase in public and private investment. Below are some issues related to the WEFE nexus governance and policies in the Indian context.

4.2.1. Nexus governance

The first step towards acting on the WEF nexus is governance, which refers to the structures and procedures needed to ensure accountability, openness, and responsiveness. Establishing policies that promote cooperation and coordination among water, energy, and food sectors and ensure cross-sectoral governance is essential. Good governance balances the trade-offs between different sectors arising due to the interaction of policies. This includes considering trade-offs and synergies between competing interests. Like most developing nations, sector-based policies and historically established, vertically organized government departments may serve as obstacles to using the nexus idea in India. The fragmented institutional framework in India that provides governance over certain aspects of the WEF nexus results in the suboptimal use of resources, which in turn causes pollution and degradation of those resources. The main obstacles to good governance are the competitive politics of subsidized water and energy in agriculture, as well as the absence of necessary interdepartmental coordination. From the governance perspective, the Nexus approach doesn't require significant restructuring or the creation of new institutional structures. What it needs is complete cooperation across entities, such as functional networks or platforms supported by multi-sector regulations, protocols, and processes (Carmona-Moreno *et al*. 2019). The 'mantra' for the success of Nexus is the intensive involvement of all the stakeholders, including scientists, decision makers, business, and industry, in identifying the research issues. Efficient governance would require putting in place a system that would make such broad involvement possible. The design of transformative changes for sustainable governance of the nexus in WEF would require an increasing role of science (Pahl-Wostl, 2017). There cannot be a fixed route for the governance of WEFE, as the administrative structure and required policy instruments will vary with scale and region. In India, land and water are state subjects and only appear on the concurrent lists of the federal government. Interstate disputes over the sharing of river water often lead to conflicts. Obviously, the solution lies in reforming the water allocation and distribution laws and restructuring the water sector administration. The government of India recently commissioned a study to look into the structural issues of water resources management (IPRS, 2016).

4.2.2. Government of India WEFE nexus policies

The policies and activities pertaining to WEFE fall under the purview of various ministries under the Government of India, which primarily operate in silos and handle related themes. The fact that different ministries exist to address different aspects of the WEFE sector shows the importance of this topic as well as the institutional barriers that may come in the way of putting into practice a comprehensive and successful WEFE plan. Furthermore, some WEFE domains, such as food and water, are encompassed in a concurrent list that engages state and federal authorities in the decision-making process. The important policies and action programs having a bearing on WEF Nexus are listed in Table 6.

As seen from Table 6, many initiatives were started in the water and agriculture sectors in recognition of the importance of irrigation to food security, with little thought given to how these initiatives might affect other sectors. Seldom was the ecosystem's impact given any thought. The outcome of some of the agriculture, water, and energy sector policies, like MSP on selected crops, a low tariff on canal waters, and almost free electricity for pumping groundwater, has adversely affected the land and water resources and the functioning of ecosystem services. The implementation of needed policy changes would require changes in the system of governance relevant for the WEFE nexus sectors.

4.2.3. Glimpses of research on policies for the WEFE nexus approach

The technologies need the wings of appropriate policies, institutions, and long-term funding to travel from labs to land at faster than business-as-usual (BAU) speeds. WEFE nexus is impacted rather highly by the phenomenon called climate change, which cannot be localized or regionalized (of course, the intensity of the impact will vary from place to place), but the whole world will have a common destiny. So is the case with national policies, which the common global policy framework will influence. It is essential to focus on the laws and policies governing resource management activities and any potential socio-economic effects or consequences. Selected studies on the impact of WEFE-centric policies and action programs are briefly discussed.

Any decision on natural resources policy inherently involves trade-offs that prevent doing just one thing, or even just positive things (First Law of Ecology). The interdependent nature of natural resources—often referred to as the water, food, and energy nexus—means that trade-offs and various effects are unavoidable. Tyagi *et al*. (2019) and Tyagi and Joshi (2019) analyzed the impact of the Government of India's policies supporting the development of the agrarian economy through the promotion of seed, irrigation, and fertilizer-centric green revolution technologies. The

Table 6. Impact of important water, agriculture and energy sectors policies/ programs on components of WEFE nexus (Adopted from Jain *et al.*, 2023).

Program/policy	Water security	Energy security	Food security	Ecosystem security
Water Sector				
Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)	P	N	P	P
Atal Bhujal Yojana (ABY)	P	P	P	P
Namami Gange Program	-	-	P	P
Bureau of Water Use Efficiency (BWUE)	P	P	P	P
Jal Jeevan Mission (JJM)	P	N	NU	N
Central Ground Water Authority (CGWA)	P	P	P	P
Agriculture sector				
National Food Security Mission	N	N	P	NU
Price Support Scheme (MSP)	P	N	P	N
Soil Health Management	P	NU	P	P
In-situ Management of Crop Residue through Mechanization	NU	N	NU	P
Sub-Mission on Agricultural Mechanization (SMAM)	NU	N	P	NU
Sub Mission on Plant Protection	P	P	P	P
Sub-Mission on Seeds and Planting Materials	P	P	P	P
Energy Sector				
KUSUM (Kisan Urja Suraksha evam Utthaan Mahabhiyan)	NU	P	NU	P
Energy use efficiency Bureau of Energy Efficiency (BEE)	NU	P	NU	P
Separation of agriculture and non-agriculture feeders	NU	P	P	NU

P=Positive impact, N=Negative impact, NU= Neutral

assessment clearly established that agricultural productivity and virtual mitigation are positively related to irrigation and fertilizers. Still, there was a high degree of trade-off regarding groundwater use, impacting the sustainability of this resource.

Jain *et al*. (2023) reviewed programs related to the WEFE nexus in India and found that while individual programs were helping to achieve policy goals and security for their respective sectors, there were notable overlaps that had both positive and negative effects on other sectors. However, no quantitative assessment of the impacts has been made. They also stressed the importance of quantifying trade-offs through modelling.

The felt need for quantitative impact assessment of WEFE-centric policies has been addressed by Modal *et al*. (2023), by analyzing the WEF nexus at the State/Union Territories (UTs) level in India using the Pardee RAND WEF Nexus Index (PR-WEFNI) for 2015-16 and 2019-20, covering twenty-nine states and seven union territories. They have proposed an indicator-based approach, i.e., a Policy Implementation Score (PIS), which indicates a policy's progress (in %), and found that States/UTs showed an increase in the Water Sub-index (WSI) and Energy Sub-index (ESI) due to higher values of the Water PIS and Energy PIS, but a decrease/no change in the Food Sub-index (FSI) due to lower Food PIS.

5. Epilogue

Even though India's sectoral WEFE policies and programs are future-focused and support the best management and conservation of the resource(s) in question, the interconnection and interdependencies between these sectors were either overlooked or not given enough thought during the policy-making process. However, the interconnection of WEFE has been acknowledged in recent years. For instance, water sector policies and programs emphasize increasing irrigation efficiency and recognize the need for irrigation sector reform to conserve water in the agricultural, urban, and industrial sectors. Similarly, low-water-use crops and crop diversification are receiving more attention in farm policies and programs. The focus on irrigation powered by solar energy illustrates the WEFE nexus in action. However, there are also worries that these systems could worsen sustainability without regulation and groundwater withdrawal increases. In any event, more strengthening of the synergies among the WEFE sectors is required. Policies on payment for ecosystem services are also missing and need to be put in place.

There have been concerted efforts in the last decade to understand the intricacies of the WEFE nexus, which have led to several conceptual frameworks and models. Despite considerable deliberations worldwide, there is little clarity on issues such as: What constitutes a successful nexus approach? How can it be achieved, monitored and evaluated, as different stakeholders, who compete for resources, have conflicting views? Few actual case studies have employed a nexus approach on a large scale, particularly in India. However, the growing discourse slowly results in warnings of the social and ecological dangers of compartmentalized management.

Some of the critical issues for further research should include the following: improved simulation models to predict the consequence of planned interventions and climate change impact; the assessment of implications of WEF nexus not being scale neutral, studies need to be conducted to address issues at different scales—local, state, country, and region; impact of existing WEF related policies have environmental costs in the form of externalities, which are generally not included in the assessment, but both individuals and society as a whole is paying for them; the health of ecosystems plays a vital role in ensuring the security of WEF, and society derives several benefits from ecosystems, and therefore nature should form part of the nexus studies. Satellite data could help rapidly assess the value of ecosystem services. Techniques for using satellite data to provide inputs for estimating variables like water, energy and nutrition accounting on different scales should be developed. Creating a cohesive framework for nexus research is crucial to achieving shared, goal-oriented solutions. This framework should be shared among project members and society stakeholders to develop integrated methods integrating mono-disciplinary research results and understand the complexities of water–energy–food systems to contribute to reducing trade-offs and increasing synergies of these WEF uses. Group model building through participatory engagement should be encouraged to ensure that stakeholders in the water, energy, and food sectors understand the importance of the WEFE inter-linkages. Similarly, the adaptable framework should be developed to take care of the diversity of resources, natural conditions, scales, levels, government, and planning systems framework, which should have the flexibility to adapt to a diverse set of circumstances in India.

Lastly, managing water resources is inherently political, and the scarcity brought on by climate change will only intensify this political aspect. Incorporating climate-wise water resources management into development plans is the most efficient approach to inspire policymakers. This will require a study on producing compelling empirical evidence and setting up efficient lines of communication with the policymakers.

6. References

Bhattarai, M., Sakthivadivel, R., & Hussain, I. (2002). Irrigation impacts on income inequality and poverty alleviation: Policy issues and options for improved management of irrigation systems (Working Paper 39). International Water Management Institute.

Carmona-Moreno, C., Dondeynaz, C., & Biedler, M. (Eds.). (2019). Position paper on water, energy, food and ecosystems (WEFE) nexus and sustainable development goals (SDGs).

Central Ground Water Board (CGWB). (2023). National compilation on dynamic groundwater resources of India, 2023. Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, Government of India.

Food and Agriculture Organization of the United Nations (FAO). (2014). The water–energy–food nexus: A new approach in support of food security and sustainable agriculture (p. 20). http://www.fao.org/3/a-bl496e.pdf

Hasnip, N., Mandal, S., Morrison, J., Pradhan, P., & Smith, L. (2001). Contribution of irrigation to sustaining rural livelihoods: Literature review. HR Wallingford and Department of International Development, UK.

Hoff, H. (2011). Understanding the nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute. http://wef-conference.gwsp.org/fileadmin/documents_news/understanding_the_nexus.pdf

Howden, S. M., Crimp, S., & Nelson, R. N. (2010). Australian agriculture in a climate of change. In 'Managing Climate Change: Papers from GREENHOUSE2009 Conference'. (Eds I Jubb, P Holper, W Cai) pp. 101–112. (CSIRO Publishing: Melbourne)

Institute for Policy Research Studies (IPRS). (2016). Restructuring the Central Water Commission and the Central Ground Water Board. PRS Legislative Research. http://www.prsindia.org/administrator/uploads/general/1472705816_Report%20Summary-%20Restructuring%20CWC.pdf

Jain, S. K., Sikka, A. K., & Alam, M. F. (2023). Water-energy-food-ecosystem nexus in India—A review of relevant studies, policies, and programs. Frontiers in Water, 5, Article 1128198. https://doi.org/10.3389/frwa.2023.1128198

Malakar, A., & Cooper, J. A. (2022). Nanotechnology at the juncture of water, food, and energy nexus: Boon or bane? In C. Ray, S. Muddu, & S. Sharma (Eds.), Food, energy, and water nexus (pp. xxx–xxx). Springer. https://doi.org/10.1007/978-3-030-85728-8_13

McNally, A., McCartney, S., Ruane, A. C., Mladenova, I. E., Whitcraft, A. K., Becker-Resher, I., Bolten, J. D., Peters-Lidard, C. D., Rosenzweig, C., & Schollaert Uz, S. (2019). Hydrologic and agricultural Earth observations and modeling for the water-food nexus. Frontiers in Environmental Science, 7, 23. https://doi.org/10.3389/fenvs.2019.00023

Muller, M. (2015). The “nexus” as a step back towards a more coherent water resource management paradigm. Water Alternatives, 8, 675–694.

Narayanamoorthy, A., & Bhattarai, M. (2004). Can irrigation increase agricultural wages? An analysis across Indian districts. Indian Journal of Labour Economics, 47(2), 251–268.

Narayanamoorthy, A. (2007). Does groundwater irrigation reduce rural poverty? Evidence from Indian states. Irrigation and Drainage, 56(2-3), 349–362.

NITI Aayog. (2023). India energy security scenarios (IESS) 2047 V3.0. Government of India. https://www.iess2047.gov.in

NITI Aayog. (2024). Working group report on crop husbandry, agriculture inputs, demand & supply. https://www.niti.gov.in/sites/default/files/2024-02/Working%20Group%20Report%20on%20Demand%20%26%20Supply%20Final_V9.pdf

Price Waterhouse Coopers (PWC). (2024). India@2047. https://www.pwc.in/research-and-insights-hub/immersive-outlook/india-at2047.html#:~:text=India%20has%20created%20a%20strong,achieved%20on%20the%20basis%20

Ram, R., & Mothkoor, V. (2022). Future roadmap of India’s energy sector. https://egov.eletsonline.com/2024/02/future-roadmap-of-indias-energy-sector/#:~:text=Growing%20Energy%20Demand%3A%20Energy%20needs,12%2C547%2D13%2C477%20kWh%20by%202047

Schipper, E., & Lisa, F. (2009). Adapting to climate change in developing countries: Institutional and policy responses for urbanizing societies (Background paper – World Economic and Social Survey). United Nations. https://www.un.org/en/development/desa/policy/wess/wess_bg_papers/bp_wess2009_schipper.pdf

Saleth, R. M. (1996). Water institutions in India: Economics, law and policy. Commonwealth Publishers.

Saleth, R. M., Samad, M., Molden, D., & Hussain, I. (2003). Water, poverty and gender: A review of issues and policies. Water Policy, 5(5-6), 385–398.

Simpson, G. B., Jewitt, G. P. W., Becker, W., Badenhorst, J., Masia, S., Neves, A. R., Rovira, P., & Pascual, V. (2022). The water-energy-food nexus index: A tool to support integrated resource planning, management and security. Frontiers in Water, 4, 825854. https://doi.org/10.3389/frwa.2022.825854

Srivastava, S. K., Ghosh, S., Kumar, A., & Anand, P. S. B. (2014). Unravelling spatio-temporal pattern of irrigation development and its impact on Indian agriculture. Irrigation and Drainage, 63(1), 1–11.

Tyagi, N. K., Joshi, P. K., Aggarwal, P. K., & Pandey, D. (2019). Role of development policies in combating climate change issues in Indian agriculture: An assessment of irrigation and fertilizer policies. In B. D. Pal *et al*. (Eds.), Climate smart agriculture in South Asia (pp. xxx–xxx). Springer Nature Singapore. https://doi.org/10.1007/978-981-10-8171-2_10

Tyagi, N. K., & Joshi, P. K. (2019). Harmonizing the water–energy–food nexus in Haryana: An exploration of technology and policy options. INAE Letters, 4, 251–267. https://doi.org/10.1007/s41403-019-00079-5

Tyagi, N. K. (2020). Managing water-energy-food security nexus under changing climate: Implementation challenges and opportunities in India. Transactions of the Indian National Academy of Engineering. https://doi.org/10.1007/s41403-020-00117-7

United Nations. (2002). World Summit on Sustainable Development (WSSD), Johannesburg Summit, Johannesburg, South Africa, 26 August - 4 September 2002. https://sustainabledevelopment.un.org/milesstones/wssd

United Nations. (2022). World population prospects 2022. Department of Economic and Social Affairs, Population Division. https://population.un.org/wup/

Vaidyanathan, A. (1999). Water resources management: Institutions and irrigation development in India. Oxford University Press.

11 Digital Agriculture

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1. Introduction

Agriculture in India is a foundation of the economy, supporting approximately half of the workforce and contributing significantly to the GDP (Economic Survey 2022-23). With diverse climatic and soil conditions, India boasts a wide range of crops including rice, wheat, sugarcane, cotton, pulses, fruits, and vegetables. However, the sector grapples with challenges such as fragmented land holdings (Islam and Rahman, 2022), water scarcity (Kulkarni *et al.*, 2023), low mechanization (Mehta *et al.*, 2023), and vulnerability to climate change (Hazarika *et al.*, 2024). Government policies play a crucial role in supporting farmers through subsidies and price support mechanisms, but issues like low income levels and indebtedness persist. Embracing technological interventions and sustainable practices is becoming increasingly important to enhance productivity, minimize environmental impact, and ensure long-term resilience. Despite challenges, agriculture remains pivotal for India's food security, rural livelihoods, and economic growth.

Digital technology refers to electronic tools, systems, devices, and resources that generate, store, or process data in digital form. It involves the use of computers, mobile devices, software, applications, and the internet to perform wide range of tasks. It is fundamentally reshaping agriculture, offering transformative solutions to address the challenges faced by farmers worldwide. Through precision agriculture techniques utilizing GPS, drones (Sahoo *et al.*, 2024), and satellite imagery, farmers can optimize resources and enhance crop yields while minimizing environmental impact. Real-time data collection from sensors and Internet of Things (IoT) devices enables

[1] ICAR-Indian Agricultural Statistics Research Institute, New Delhi
[2] Fertilizer Association of India, New Delhi

data-driven decision-making, digital monitoring, empowering farmers to make informed choices regarding irrigation, pest management, and crop rotation (Farooq *et al.*, 2020; Subeesh and Mehta, 2021; Tasgonkar and Cihan, 2024; Chakrabarty *et al.*, 2024). Digital platforms provide farmers with access to market information, weather forecasts, financial services, fostering financial inclusion and improving market access (Sizan *et al.*, 2025); Blockchain technology ensures transparency and traceability in supply chains, enhancing food safety and reducing waste (Kamilaris *et al.* 2019). Additionally, digital tools offer capacity building and extension services, enabling farmers to adopt modern agricultural practices and build resilience to climate change. Embracing digital innovation is critical for the sustainable development of agriculture, ensuring food security, and improving the livelihoods of farmers worldwide (Islam *et.al.*, 2025).

The purpose of a vision for 2047 is to provide a long-term strategic roadmap for the nation, organization and community, outlining its aspirations, goals, and priorities for the future. This vision serves as a guiding framework to inspire action, drive progress, and rally stakeholders towards a common vision of the future. By setting ambitious yet achievable targets, the vision for 2047 aims to foster sustainable development, economic growth, social cohesion, and environmental stewardship. It also serves as a tool for decision-makers to align policies, investments, and initiatives towards realizing the desired future state. Additionally, the vision for 2047 acts as a source of motivation and hope, encouraging individuals and groups to contribute towards building a better and brighter future for generations to come.

2. Current Landscape of Indian Agriculture

Indian farmers confront a myriad of challenges that undermine their livelihoods and productivity. These include fragmented land holdings, water scarcity impaired by inadequate irrigation infrastructure, rising input costs, and the persistent threat of pests and diseases. Climate change-induced erratic weather patterns further intensifies these challenges, posing a severe risk to agricultural productivity and food security. Moreover, farmers often face market risks due to price volatility and limited access to markets, while debt and financial distress are pervasive issues, leading to tragic outcomes in some cases. Inadequate infrastructure, including storage and transportation facilities, exacerbates post-harvest losses, while limited access to information and technology hampers productivity improvement. Addressing these multifaceted challenges necessitates comprehensive policy interventions, investments in infrastructure and technology, access to finance, and support for sustainable agricultural practices to ensure the well-being and prosperity of Indian farmers. Various technologies are being deployed in Indian agriculture to address challenges and improve productivity. These include drip irrigation systems, solar-powered pumps to optimize water use (Abdelhamid *et al.*, 2025), precision farming techniques utilizing GPS and drones for efficient crop management (Vellingiri, A *et al.*, 2025; Das, N *et al.*, 2025), and mobile applications providing farmers with access to market information and advisory services (Adla *et al.*, 2025; Mukherjee *et al.*, 2025). Biotechnological advancements such as genome-edited crops enhance resilience (Riaz *et al.*, 2025), while mechanization with modern farming equipment reduces labour costs and increases efficiency. Remote sensing technologies aid in crop monitoring and pest management, and soil health management tools ensure sustainable soil fertility. Additionally, post-harvest technologies like solar dryers and cold storage facilities minimize losses and maintain produce quality. These technologies collectively contribute to modernizing Indian agriculture, improving farmer livelihoods, and ensuring food security for the nation. Continued investment in research and adoption of innovative technologies remains critical for the sector's sustainable growth.

Traditional farming methods in India face numerous limitations that hinder agricultural productivity and sustainability. These methods heavily rely on unpredictable monsoon rains for irrigation, making crops vulnerable to droughts and climate variability. Additionally, low mechanization, unbalanced use of inputs like fertilizers and pesticides, and inefficient water management contribute to low crop yields. Continuous cultivation without proper soil conservation measures leads to soil erosion, degradation, and reduced fertility. Moreover, traditional farming practices often focus on a limited variety of crops, leading to monoculture farming and increased susceptibility to pests, diseases, and market fluctuations. Labour-intensive techniques are not only time-consuming and costly but also contribute to the migration of rural labour. Inadequate storage facilities and post-harvest handling practices result in significant losses of agricultural produce, impacting farmer incomes. Limited access to information, technology, credit, and insurance further intensifies financial instability among traditional farmers. These challenges highlight the urgent need for promoting sustainable farming practices through digital infrastructure, investing in modern technologies, improving access to resources and market information, and providing policy support to enhance the resilience and livelihoods of Indian farmers.

3. Global Trend in Digital Agriculture

The global digital agriculture industry, valued at USD 22.0 billion in 2023, is poised for substantial growth, projected to reach USD 36.0 billion by 2028 with a robust compound annual growth rate (CAGR) of 10.3% (MarketsandMarkets, 2024). This trend signifies a transformative force revolutionizing farming practices, enhancing efficiency, sustainability, and resilience against evolving challenges. Advancements in technologies like the Statistical Data Science (Parsad *et al*., 2024), Internet of Things (IoT), Artificial Intelligence (AI), drones, and satellite imagery provide farmers with real-time data, enabling farming practices for monitoring crop health, optimizing irrigation, and detecting pest infestations accurately. Digital agriculture leverages big data analytics (NAAS, 2021, Policy paper 101) to analyse weather patterns, soil quality, and crop performance, empowering farmers to make informed decisions regarding crop selection, planting strategies, and resource allocation, leading to improved productivity and sustainability. Precision agriculture practices, facilitated by digital tools, involve precise application of inputs such as fertilizers, pesticides, and water based on localized conditions, minimizing waste and maximizing yields. Farm management software platforms streamline administrative tasks, inventory management, and facilitate communication among stakeholders. Additionally, digital solutions enhance market access for farmers through online trading platforms and provide traceability systems ensuring transparency throughout the supply chain. Amidst climate change challenges, digital technologies offer adaptive solutions with smart climate monitoring systems and climate-smart farming practices, empowering farmers to optimize production sustainably. India, as one of the fastest-growing markets for digital agriculture in the Asia Pacific region, integrates Artificial Intelligence, robotics, sensors, and communication networks into farms (agriculture, horticulture, animal, fisheries), driving remarkable improvements in productivity, yields, food grading, and decision-making capabilities.

4. Present Status of Digital Agriculture in India

As of the present, digital agriculture in India has seen significant advancements driven by the proliferation of digital platforms, precision agriculture techniques, and government initiatives. These platforms have facilitated market linkages, financial inclusion, and access to information and advisory services for farmers. Precision agriculture tools, including remote sensing and IoT, are enhancing crop management practices, livestock and aquaculture monitoring and management systems, while data analytics and AI are providing valuable insights for decision-making. Mobile applications have become essential tools for farmers, offering a range of services from weather forecasts, plant protection advisories to market prices. Despite progress, challenges such as digital literacy, connectivity issues, and affordability persist, highlighting the need for continued efforts to ensure inclusive and sustainable growth in the sector.

5. Past, Present and Future of Digital Agriculture

Indian Council of Agricultural Research (ICAR) has always been at the forefront of digital initiatives in the country and over the years, the adoption of Information and Communication Technology (ICT) has played a transformative role in enhancing research, education, extension and governance within ICAR institutions. 1964, Indian agriculture marked a historic milestone with the introduction of its inaugural computer, the IBM 1620 Model-II Electronic Computer at ICAR-Indian Agricultural Statistics Research Institute (ICAR-IASRI). The installation process commenced, paving the way for a ground-breaking era in the realm of statistical computing and digital agriculture. After that installation of the third-generation computer system, the Burroughs B-4700, took place, heralding a new era in computing technology. The launch of the Agricultural Research Information System (ARIS) marked one of the early milestones in integrating ICT into ICAR's operations. ARIS now known Agricultural Knowledge Management Unit (AKMU) aimed to improve the data management across ICAR institutions, setting the foundation for subsequent technological advancements.

After that a series of significant changes happened in all the dimension of digital agriculture, the domain experts felt the importance of expert system and information systems. Several online and desktop analytical tools have been released, like Design Resources Server, Sample Survey Resources Server, Strengthening Statistical Computing for National Agricultural Research System, National Bio-computing Portal, and other similar tools/platforms that accelerated the speed of data processing, analysis, and visualization, ultimately streamlining evidence based decision-making processes and enhancing overall efficiency in various fields such as research, business intelligence, and academic studies. Creation of Advanced Supercomputing Hub for Omics in Agriculture (ASHOKA), establishment of ICAR Data Centre, starting AI research using GPU system was not only futuristic but also served for the present demand. Presently, ICAR is well equipped with digital infrastructure, software solutions, and data repository that with continuous strengthening can help in establishment of futuristic digital ecosystems. KRISHI (Agricultural Knowledge Resources and Information System Hub for Innovations) is a significant initiative by the ICAR to create a centralized research data repository to streamline data collection, sharing, and analysis across its vast network of institutions. Network Project of Precision Agriculture (NePPA) is another initiative that focuses on developing ICT-based tools, sensors, and AI-driven solutions for soil fertility, crop health, irrigation, livestock and fisheries management to develop research models to enhance productivity, resource efficiency, and sustainability in farming systems. NADRES V2 National Animal Disease Referral Expert System Version 2 (NADRES V2) is an advanced platform by ICAR-NIVEDI for forecasting and mapping livestock disease risks across India.

ICAR has launched key digital initiatives in fisheries, including the National Fisheries Digital Platform (NFDP), drone-based live fish transport (ICAR-CIFRI), and satellite-based Potential Fishing Zone (PFZ) forecasting with ISRO (ICAR-CMFRI) to enhance productivity and sustainability (Kumar, 2020; Department of Fisheries, 2024). These are supported by schemes like PM-MKSSY (Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana) for broader tech adoption.

In the present day, futuristic AI has integrated seamlessly into various facets of daily life, showcasing remarkable advancements across multiple domains. Impetus to AI in ICAR was provided by a National Workshop on AI in Agriculture held during 2018 (Bhar *et al*., 2019). Conversational AI interfaces now exhibit unprecedented natural language understanding, smoothly interpreting context and emotions in human communication. Personalized AI assistants have become indispensable, intuitively anticipating user needs and preferences. Breakthroughs in deep learning techniques have revolutionized AI capabilities, enabling more efficient learning from limited data and enhanced generalization across tasks. Livestock healthcare has witnessed a profound transformation with AI aiding in diagnosis, treatment planning, and personalized medicine. Autonomous vehicles may navigate our streets confidently, powered by AI perception and decision-making systems. Ethical considerations and regulations surrounding AI development and deployment are receiving heightened attention to ensure responsible usage. From fostering creativity and innovation to driving automation in agriculture, futuristic AI continues to shape the world, tackling challenges in climate change and sustainability while addressing governance and security concerns in the digital landscape. The power of AI is already been put to use through mobile apps such as AI-DISC, AI-DISA and others for identification of disease and pest detection in crops, animal diseases; CHATBOTS, smart pheromone trap for real-time monitoring of cotton pink bollworm, etc. (Arora *et al*., 2025). Several other NARS organizations have been involved in developing AI based applications.

The described futuristic trend suggests a seamless integration of AI in digital agriculture. In the near future, farmers will benefit from personalized digital assistants capable of providing tailored and customized advice and recommendations based on their specific land, crops, and socio-economic conditions. Additionally, farmers will have access to market intelligence at their fingertips every morning, aiding in informed decision-making regarding market trends. IoT-enabled mechanization will address labour shortages while improving the precision and efficiency of harvesting and post harvesting tasks.

6. Vision for Digital Agriculture in India by 2047

The integration of emerging digital technologies is revolutionizing agriculture in India, propelling the sector towards greater efficiency and sustainability. IoT is being leveraged for smart farming practices, where sensors and connected devices monitor soil moisture, temperature, and crop health in real-time, enabling precise resource management. AI is powering predictive analysis, using data from IoT sensors, camera images and historical patterns to forecast weather, pest outbreaks, and optimal planting time and empowering farmers to make informed decisions. Blockchain technology is ensuring transparent transactions in agricultural supply chains, enhancing trust and traceability from farm to fork, while also tackling issues of fraud and counterfeit products. Robotics is transforming farming operations with automated solutions for tasks like planting, weeding, and harvesting, reducing labour costs, increasing productivity, post-harvest management and value addition. As these technologies converge, they are reshaping the agricultural landscape in India, driving innovation and sustainable growth in the sector.

Data-driven decision-making is becoming increasingly prevalent in Indian agriculture, empowering farmers with valuable insights to optimize productivity and mitigate risks. Precision farming techniques utilize data from various sources, including satellite imagery and soil sensors, to tailor inputs such as water, fertilizers, and pesticides to specific crop requirements, maximizing yields while minimizing resource wastage. Weather forecasting plays a crucial role in risk management, allowing farmers to anticipate extreme weather events and plan accordingly, whether it's adjusting planting schedules or implementing protective measures. Crop, livestock and fish health monitoring through data analytics enables early detection of diseases and pests, facilitating timely interventions to prevent productivity loss. By harnessing the power of data, Indian farmers are making informed decisions that drive efficiency, resilience, and sustainability in agricultural practices.

Sustainable practices are gaining momentum in Indian agriculture, with a focus on conserving resources, reducing carbon footprint, and embracing organic farming methods. Technology plays a crucial role in resource conservation, with tools like drip irrigation and precision farming techniques, AI empowered sprayers, optimizing water, fertilizer and pesticide usage, minimizing waste while maximizing crop yields. Additionally, the adoption of renewable energy sources and efficient machinery helps reduce the carbon footprint of farming operations, contributing to environmental preservation. By integrating sustainable practices into their operations using digital means, Indian farmers are not only safeguarding natural resources but also promoting long-term agricultural resilience and ensuring a healthier planet for future generations.

Inclusivity and accessibility are essential pillars of India's agricultural transformation, ensuring that the benefits of technological advancements reach all farmers, including those in remote rural areas. Training and education programs are being implemented to empower farmers with the knowledge and skills needed to leverage digital tools and sustainable practices effectively. Efforts are also underway to improve the accessibility of technology in rural areas, addressing challenges such as connectivity issues and affordability. Government initiatives and private sector collaborations are facilitating the distribution of smartphones, internet connectivity, and agricultural apps to remote farming communities, bridging the digital divide. Additionally, support is being extended to small-scale farmers and cooperatives through access to credit, subsidies, and market linkages, enabling them to adopt modern farming practices and improve their livelihoods. By prioritizing inclusivity and accessibility, India is striving to create a more equitable and resilient agricultural sector that benefits all stakeholders.

The implementation strategy for advancing digital agriculture in India encompasses a multi-faceted approach, with key focus areas including government initiatives and policies, private sector investments and partnerships, research and development efforts, infrastructure development, and international collaborations. Government initiatives and policies play a central role in providing the necessary regulatory framework and financial support to promote digital agriculture adoption among farmers. Simultaneously, private sector investments and partnerships drive innovation and scale-up digital solutions, leveraging their expertise and resources to address specific agricultural challenges. Research and development efforts are crucial for advancing digital technologies tailored to Indian agricultural conditions, ensuring their effectiveness and relevance. Therefore, creation and strengthening of high end computational and storage infrastructure for research purpose with sustainable fund allocations is crucial. Infrastructure development, particularly in rural areas, is equally important to improve connectivity and access to digital tools and services for farmers. Lastly, international collaborations and knowledge exchange facilitate the sharing of best practices, technology transfer, and capacity building, enriching India's digital agriculture ecosystem with global insights and expertise. By integrating these strategies, India aims to accelerate the adoption of digital agriculture and unlock its potential to transform the agricultural sector, improve farmer livelihoods, and ensure transforming agri-food system.

The potential benefits of advancing digital agriculture in India are vast and far-reaching, with the promise of increased agricultural productivity, improved farmer livelihoods, enhanced food security, and sustainable environmental practices. By harnessing technology and data-driven approaches, farmers can optimize their resources more efficiently, leading to higher sustainable farm productivity with optimizing overall cost of cultivation. This increase in productivity not only boosts farmer incomes but also contributes to improved livelihoods and economic growth in rural communities. Moreover, digital agriculture enables better risk management and resilience against climate change-related challenges, thereby enhancing food and nutrition security by ensuring a steady and reliable food supply. Furthermore, the adoption of sustainable environmental practices, such as precision farming facilitated by digital technologies, promotes soil health, biodiversity, and natural resource conservation, contributing to long-term environmental sustainability. Overall, the integration of digital agriculture in India holds the potential to revolutionize the agricultural sector, benefiting farmers, consumers, and the environment alike.

7. Challenges and Mitigation Strategies

Addressing the multifaceted challenges surrounding the adoption of sustainable agricultural practices involves navigating through various obstacles. Technological barriers often hinder the widespread implementation of innovative solutions, such as precision agriculture and AI-driven farming techniques, due to issues like limited access to advanced equipment and inadequate technical expertise among farmers. To overcome this, comprehensive training programs and technical support initiatives must be implemented to empower farmers with the necessary skills and resources. Additionally, adoption hurdles among farmers can arise from factors such as initial investment costs, perceived risks, and cultural preferences for traditional farming methods. Engaging with local communities, providing financial incentives, and showcasing success stories can help incentivize farmers to embrace digital technologies and sustainable practices. Policy and regulatory challenges also play a significant role, as outdated regulations or inconsistent policies may impede the adoption of sustainable farming technologies. Therefore, governments need to develop clear and supportive policies that incentivize and facilitate the transition towards environmental-friendly agricultural practices. Socio-economic disparities further exacerbate these challenges, as marginalized communities often face greater barriers in accessing resources and information. Addressing socio-economic disparities requires targeted interventions such as access to credit, extension services, and market linkages to ensure equitable participation in sustainable agriculture initiatives. Lastly, environmental concerns, including issues such as soil degradation, water scarcity, and biodiversity loss, highlight the urgent need for sustainable agricultural practices. Implementing agroecological approaches, promoting conservation agriculture, and enhancing resource use efficiency can mitigate environmental risks and contribute to long-term sustainability in agriculture. By addressing these challenges through collaborative efforts involving policymakers, agricultural stakeholders, and local communities and effective use of digital initiatives, we can foster a more resilient and sustainable agricultural sector that meets the needs of both present and future generations.

8. Pillars of Digital Agriculture

Agricultural research, education, and extension, collectively accelerate the advancement of digital agriculture by equipping farmers and agricultural professionals with the necessary skills, knowledge, and resources. Agricultural education programs impart expertise in digital technologies relevant to farming practices, raising awareness and facilitating the adoption of emerging tools. Extension services play a pivotal role in transferring technology from research institutions to farmers, providing guidance and support throughout the adoption process. Kisan Sarathi (System of Agri-information Resources Auto-transmission and Technology Hub Interface), is a digital advisory service enabling farmers to seek expert guidance on crop cultivation, pest management, and market trends through accessible digital communication channels. Analytical platform like KCC-CHAKSHU (Kisan Call Centre-Collated Historically Aggregated Knowledge-based System with Hypertext User-interface) provides a user-friendly interface for exploring, analyzing, and visualizing the Kisan Call Centre (KCC) data. By enabling stakeholders to understand trends, map query hotspots, and access data for research, it supports informed decision-making and targeted agricultural interventions. Further analytics in terms of query-response-generation system from KCC data would facilitate the extension workers. Harnessing synergies between Common Service Centre (CSC) Ecosystem, Krishi Vigyan Kendra, Kisan Call Centres and digital extension platforms would enhance the reach of advanced agricultural technologies to the stakeholders.

Meanwhile, agricultural research drives innovation, validating and refining digital agriculture solutions to address specific challenges and enhance their applicability across diverse agricultural contexts. Through collaboration among these components, stakeholders facilitate the widespread adoption of digital agriculture, empowering farmers to harness technology for improved productivity, sustainability, and resilience in agricultural systems.

Over the past decade, the agricultural education system has experienced a significant paradigm shift with the widespread adoption of digital technologies. This transformation has seen a move away from traditional methods towards the integration of digital tools such as Academic Management Systems (AMS) to streamline and manage the entire student lifecycle. Another notable aspect of this shift is the emergence of e-learning and blended learning platforms, which have revolutionized the way students engage with educational content. These platforms have provided students with greater access to a wide range of learning materials and resources, while also empowering content creators to develop and share innovative educational content. Furthermore, the integration of Augmented Reality (AR) and Virtual Reality (VR) technologies has enhanced the agricultural education experience by making it more engaging and immersive. These technologies have allowed students to visualize complex concepts in a more interactive and intuitive manner, thereby improving their understanding and retention of scientific principles. Overall, the adoption of digital technologies has made the agricultural education system more dynamic, engaging, and scientifically rigorous. By leveraging tools such as e-learning platforms, AR and VR, educators have been able to create more effective and efficient learning environments that prepare students for the challenges of modern agriculture.

The major challenges that are being faced in implementing digital technologies in agriculture are high implementation costs, limited access to technology and information, data quality and standards, digital literacy and skill gap, resistance to change, infrastructure limitations, and challenges in consistent, accurate, reliable, and time bound availability of comprehensive data.

9. Promoting Responsible AI in Digital Agriculture: The Role of GPAI

Responsible AI in the context of digital agriculture involves using Artificial Intelligence (AI) technologies in a way that prioritizes ethical considerations, sustainability, and societal well-being. This includes ensuring fairness and transparency in AI algorithms, protecting data privacy and security, minimizing biases in AI decision-making, and considering the potential socio-economic impacts of AI adoption in agriculture.

The Global Partnership on Artificial Intelligence (GPAI) (Vanberghen and Vanberghen, 2022) is an international initiative launched to support the responsible development and use of AI. It aims to bridge the gap between theory and practice, bringing together experts from governments, industry, academia, and civil society to collaborate on AI-related issues. GPAI focuses on various AI applications, including those in agriculture, and works to develop best practices, guidelines, and policy recommendations to address emerging challenges and opportunities in the field.

In the context of digital agriculture, GPAI can play a significant role in promoting responsible AI by fostering collaboration, sharing knowledge and resources, and establishing frameworks for ethical AI development and deployment. This may involve initiatives such as developing AI-powered tools for precision agriculture, enhancing data governance and interoperability standards (following FAIR- Findable, Accessible, Interoperable and Reusable principles), and addressing ethical considerations related to AI-driven decision-making in farming practices.

Overall, responsible AI and initiatives like GPAI are essential for ensuring that AI technologies in digital agriculture are developed and deployed in a manner that benefits society while minimizing potential risks and harms. By promoting collaboration and ethical guidelines, these efforts can help unlock the full potential of AI in agriculture while addressing concerns related to fairness, transparency, and sustainability.

10. A Futuristic Projection of Digital Agriculture

In the future of digital agriculture, farms will be transformed into high-tech hubs of innovation, where precision and efficiency reign supreme. IoT sensors embedded throughout the landscape will continuously monitor soil, crop, livestock, fish farms and equipment data, feeding it into advanced analytics and machine learning algorithms. Autonomous drones and machinery will navigate fields with precision, performing tasks like planting, fertilizing, and harvesting with unparalleled efficiency. Farmers will make data-driven decisions, leveraging insights from massive datasets to optimize planting schedules, irrigation, and pest management. Vertical and urban farming will flourish, using controlled environments to maximize yields in limited space. Blockchain technology will ensure transparent and traceable supply chains, while gene editing advances will create resilient and nutritious crops. Using machine leaving and AI, the genes to be edited will be identified. Augmented reality will empower farmers with real-time guidance, while predictive analytics models will enhance climate resilience. Collaboration platforms will foster knowledge-sharing among farmers worldwide, promoting sustainable practices and environmental stewardship. Ultimately, digital agriculture promises to revolutionize food production, ensuring global food security while promoting sustainability in the face of evolving challenges.

The future of computing in agriculture and AI will likely be a hybrid ecosystem, involving quantum computing (Singh and Khan, 2023) for specific high-complexity problems, while parallel, distributed, and edge computing will continue to power large-scale data processing and real-time AI applications. These algorithms can extract valuable insights from agricultural data, such as soil composition, weather patterns, and crop genetics, to inform decision-making processes in areas like crop management, genetic analysis, and supply chain optimization (Basit *et al.*, 2025). By leveraging the capabilities of advanced computing real-time monitoring and decision-making in precision agriculture will be far more efficient resource usage, enhanced crop yields, and improved sustainability. Such integration has the potential to transform agriculture into a data-driven, highly optimized industry capable of addressing the challenges of feeding a growing global population while minimizing environmental impact.

10.1. Advanced data analytics

Extracting meaningful insights from available datasets, farmers and agricultural scientists can make informed decisions to optimize farming practices for improved productivity and sustainability. The future of this field may bring the following advancements:

- Integration of statistical learning, artificial intelligence and machine learning.
- Handling of big data with distributed computing frameworks.
- Demand for real-time analytics due to IoT proliferation.
- Importance of data visualization for communication and interpretation.
- Emphasis on data privacy, security, and compliance.
- Automation of data preparation tasks.
- Focus on explainable AI for transparency and interpretability.
- Growth of edge computing for real-time analytics at the edge of the network.
- Adoption of collaborative and agile methodologies.
- Enhanced awareness of ethical considerations in data analysis.

10.2. Precision farming

Real-time monitoring of crop health, soil moisture levels, and pest infestations can be facilitated with high accuracy. Advanced data analytics can analyze streaming data from sensors deployed across fields/ farm to collect data on various parameters like soil moisture, nutrient levels, and crop, animal and fish health etc., providing farmers with timely insights to adjust irrigation schedules, apply fertilizers precisely, and mitigate crop/ livestock/fish diseases. Based on data insights, variable rate technology enables the targeted application of resources such as water, fertilizers, and pesticides, ensuring that only the necessary amounts are applied to specific areas. This can help reduce waste, improve yields and quality, and save costs. This precision approach minimizes resource wastage and maximizes yield efficiency. The future of this field may bring the following advancements:

- Advanced and cost-effective sensor technology
- Data analytics and AI

- Precision application technologies
- Automated machinery and integration of robotics
- Remote monitoring and control
- Blockchain and IoT integration
- Climate-smart solutions
- Collaborative platforms
- Policy support and investment

10.3. Genetic analysis and crop improvement

Knowledge can expedite the development of genetically enhanced crops tailored to specific environmental conditions, ultimately contributing to global food security. There is also a need for methods, models, and hardware/software solutions for creating and actualization of digital clones of crops that ensure the possibility to perform virtual biological experiments with evaluation and forecasting of parameters that have an effect for the further field setting and adaptation of plants in conditions of natural environment and climatic factors. The following advancements are expected in this area:

- *Integration of large-scale multi-omics datasets*—including phenomics, genomics, transcriptomics, proteomics, metagenomics, and metabolomics—for comprehensive analysis and informed breeding strategies.
- *Digital twin technology* for simulating stress environments and their effects on phenotypic traits, allowing for early-stage testing and optimization of crop traits without physical field trials.
- *Advanced computational techniques* such as parallel computing, edge computing, and AI-driven modeling for processing complex biological data and running high-throughput simulations.

10.4. Supply chain optimization

The major gaps in agricultural Supply Chain Management (SCM) in India are: fragmented supply chains, post-harvest losses, seasonality and price volatility, lack of cold chain infrastructure and limited access to information. Warehouse receipt system, e-commerce platforms, promoting the use of technology like mobile apps, data analytics, and precision agriculture can improve farm management practices, optimize resource use, and connect farmers with valuable market information would improve SCM. AI based hand held devices measuring the quality of farm produce would enhance transparency in marketing system. However, all this require, in-depth computing. The following advancements are expected in the area:

- AI and Machine Learning Integration
- Blockchain Technology Implementation
- Internet of Things (IoT) Integration
- Predictive Analytics Adoption
- Sustainable Green Computing
- Real-time Tracking and Visibility
- Autonomous Vehicles and Drones
- 3D Printing and Additive Manufacturing
- Demand Sensing and Forecasting
- Collaborative Platforms and Partnerships

10.5. Climate resilience and environmental sustainability

By harnessing the power of quantum machine learning, farmers can adapt their practices to mitigate the impacts of climate change. Quantum algorithms can analyze climate models and historical weather data to predict extreme weather events and optimize planting schedules accordingly. Moreover, by optimizing resource usage and reducing waste, quantum-enabled agriculture contributes to environmental sustainability by conserving water, minimizing chemical inputs, and preserving biodiversity. The following advancements are expected to happen in the area:

- Technological advancements: Continued development of renewable energy and carbon capture technologies.
- Green infrastructure: Investments in projects like green roofs and urban green spaces to adapt to climate change and enhance biodiversity.
- Policy initiatives: Implementation of measures such as carbon pricing and regulations to protect ecosystems, supported by international agreements.
- Corporate sustainability: Increasing adoption of sustainability initiatives by businesses to reduce environmental impact and ensure long-term viability.

- Community resilience: Building resilience at the community level to protect vulnerable populations from climate change impacts and extreme weather events.
- Behavioral changes: Encouraging individuals to adopt sustainable behaviors like reducing energy consumption and minimizing waste.

10.6. Global collaboration and knowledge sharing

This collaborative approach fosters innovation and accelerates the adoption of advanced farming techniques, benefiting farmers worldwide.

10.7. Economic empowerment of farmers

Digitalization is a powerful tool for promoting financial inclusion in agriculture, particularly in developing countries, where smallholder farmers often lack access to formal financial services. Success of Unified Payment Interface (UPI) in India, which is a fast and secure payment system, used largely for peer-to-peer and peer-to-merchant retail payment system in India is quite motivational for adoption of digital platforms of financial inclusion in agriculture. In order to improve financial inclusion in Indian agriculture, a multi-pronged approach that addresses credit availability, financial literacy, and digital access is essential. By working together, the government, financial institutions, and fintech companies can empower farmers and unlock the true potential of the agricultural sector.

11. Roadmap of the Digital Agriculture for 2047

The roadmap for digital agriculture necessitates multiple reinventions of digital technology and its utilization. The remarkable advancements in information technology and biotechnology, coupled with paradigm of data discovery in agriculture, shifts in computing {CPU (Central Processing Unit) to GPU (Graphics Processing Unit), TPU (Tensor Processing Unit) and then Quantam Processing Unit} driven by the introduction of AI, make it increasingly challenging to accurately predict the actual changes and challenges that will emerge in the future. However, it is certain that by 2047, there will be another paradigm shift in development. It is highly likely that 2047 will witness the onset of the "Automation Revolution". This revolution will need new inputs, may cause some job losses, but will also create many new opportunities. By 2047, the ecology will also directly be impacted by the digital technology. The roadmap may depend on the 8 P's as follows.

11.1. People

The creation of a large number of competent people for absorbing and be absorbed by the automation revolution involving human like intelligence. Roping in volunteers for digital agriculture to strengthen the last mile connectivity. Students, scientists, policy makers and farmers need to be equipped with new skills and tools of digital agri-food systems through continuous capacity building programmes. Promoting creation of entrepreneurship program for rural youth for custom hiring, operational management, and maintenance of digital technologies/equipment at the village level along the lines of the Common Service Centre (CSC) is also required.

11.2. Predictive analytics

Leveraging data analytics and predictive modeling allows farmers to anticipate crop diseases, pest infestations, livestock diseases and adverse weather conditions. By identifying potential risks in advance, farmers can take proactive measures to mitigate them, leading to more resilient and productive agricultural systems. Achieving this, however, requires high-quality and accurate data. Strengthening of centralized data acquisition, collection, collation for developing digital tools with standardized formats and protocols for quality data following FAIR principle along with advanced analytics would help to assimilate, interpret, innovate and adapt for smart farming. Statistical data analytics, data science, artificial intelligence, machine learning, robotics, digital means of dissemination of agricultural technologies, centralized data repositories, learning management system, large language models and use of virtual reality modules in agricultural research and education need greater emphasis.

11.3. Precision farming

Utilizing precision farming techniques enables farmers to optimize the use of resources such as water, fertilizers, and pesticides by applying them exactly where and when they are needed. This approach reduces waste, minimizes environmental impact, and maximizes crop yields. The integration of IoT and sensor technologies in digital agriculture makes this precision possible. Models developed for predictive analytics and image analysis should be integrated with farm equipment, livestock management systems, and aquaculture pond management.

11.4. Plant breeding

Investing in plant breeding programs focused on developing climate-resilient and high-yielding crop varieties can help mitigate the impact of changing environmental conditions on agricultural productivity. Incorporating traits such as drought tolerance, disease resistance, and nutritional value can enhance crop resilience and adaptability. High-throughput plant phenotyping can significantly accelerate the process of assessing plant traits, thereby supporting rapid advancements in crop improvement and research. Predictive analytics and AI can identify the genes responsible for favourable traits in crops, livestock, fisheries and micro organisms.

11.5. Policy support

Enacting supportive policies at the local, national, and international levels can facilitate the adoption of digital technologies in agriculture. This includes providing financial incentives, research funding, and regulatory frameworks that encourage innovation, investment, and knowledge sharing in the agricultural sector.

11.6. Partnerships and collaboration

Encouraging collaboration among stakeholders, including farmers, researchers, technology developers, government agencies, and private sector organizations, fosters the exchange of expertise, resources, and best practices. Inter-disciplinary and inter-stakeholder collaborations (inclusiveness with Public-Private-Peasants-Partnership model) to scale up digital infrastructure and improve informatics & sharing culture in agriculture systems, which will help in more innovations and open solutions. Hub and spoke model framework of collaboration is the key to development of technologies/framework for digital agriculture. Collaborative efforts can accelerate the development and adoption of digital solutions tailored to the needs of farmers and agribusinesses.

11.7. Public awareness and education

Raising awareness among farmers and agricultural communities about the potential benefits of digital technologies and providing training and education programs to enhance digital literacy and skills are crucial for successful adoption. Empowering farmers with knowledge and resources enables them to make informed decisions and effectively utilize digital tools to improve farm management practices.

11.8. Protection of data privacy and security

Implementing robust data privacy and security measures safeguards sensitive information collected through digital agriculture technologies, such as farm management systems and IoT devices. Ensuring data integrity and confidentiality builds trust among stakeholders and encourages widespread adoption of digital solutions.

12. Epilogue

The vision for advancing agriculture in India through digitalization by 2047 presents a comprehensive roadmap for transforming the sector towards greater efficiency, sustainability, and resilience. By harnessing the power of emerging technologies such as IoT, AI, blockchain, and robotics, Indian agriculture can overcome longstanding challenges and unlock its full potential for the benefit of farmers, consumers, and the environment.

The document outlines the current landscape of Indian agriculture, highlighting the challenges faced by farmers and the transformative potential of digital technologies. It discusses the global trend in digital agriculture, emphasizing the rapid growth and adoption of innovative solutions worldwide. Furthermore, it assesses the present status of digital agriculture in India, acknowledging the progress made while identifying remaining challenges such as digital literacy and connectivity issues. Enabling ICT infrastructure with adequate funding for timely upgradation, maintenance and for long term sustainability is the key for advancement in digital agriculture. Improving rural infrastructure, digital literacy in regional languages, support agri-tech innovations, integrate tools such as e-NAM, block chain, AI, IoT, satellite data, and specialized digital marketplaces would help to improve market access, transparency, and supply-chain efficiency. The translation of output of research efforts into user friendly applications for ease of doing business would provide the needed strive for reaching to stakeholders.

The vision for digital agriculture in India by 2047 envisions a future where farmers have access to cutting-edge technologies and data-driven insights that empower them to optimize resource management, improve productivity, and enhance market access. Sustainable practices, inclusivity, and accessibility are prioritized to ensure that the benefits of digitalization reach all farmers, including those in remote rural areas.

Challenges surrounding the adoption of sustainable agricultural practices are addressed, with mitigation strategies proposed to overcome barriers such as technological limitations, adoption hurdles, policy and regulatory challenges, socio-economic disparities, and environmental concerns. The importance of agricultural education, research, and extension has been highlighted in accelerating the advancement of digital agriculture, as well as the role of initiatives like the GPAI in promoting responsible AI in the sector. Ensuring intellectual property rights in AI and other digital technologies are also of paramount importance. Finally, a futuristic projection of digital agriculture paints a picture of farms transformed into high-tech hubs of innovation, where precision, efficiency, and sustainability drive food production to ensure global food security in the face of evolving challenges.

Overall, the vision for advancing agriculture in India through digitalization by 2047 offers a compelling narrative of progress and possibility, serving as a guiding framework for policymakers, stakeholders, and farmers to work towards a more resilient, sustainable, and prosperous agricultural sector.

13. References

Abdelhamid, M. A., Abdelkader, T. K., Sayed, H. A., Zhang, Z., Zhao, X., & Atia, M. F. (2025). Design and evaluation of a solar powered smart irrigation system for sustainable urban agriculture. *Scientific Reports*, 15(1), 11761.

Adla, S., Aravindakshan, A., Tyagi, A., Guntha, R., Ponce-Pacheco, M. A., Nagi, A., ... & Pande, S. (2025). Participatory development of mobile agricultural advisory driven by behavioural determinants of adoption. *Journal of Environmental Management*, 374, 124140.

Arora, A., Deb, C.K., Misra, T., Chaurasia, H., Marwaha, S. & Parsad, R. (2025). Advancing Toward Sustainable Agriculture Through Artificial Intelligence: Case Studies in Indian Agriculture. In: *Advances in Agri-Food Systems Volume I*: Eds.Himanshu Pathak, W.S. Lakra, A. Gopalakrishnan and K. C. Bansal. 273-286. ISBN 978-981-96-0758-7. Springer Nature Singapore Pte Ltd.

Basit, J., Arshad, H., & Bibi, A. (2025). Optimizing crop yield forecasts using quantum machine learning techniques with high-dimensional soil and weather data. *Journal of Computers and Intelligent Systems*, 3(1), 01-15.

Bhar, L.M., Ambast, S.K., Soam, S.K. and Srinivasa Rao, Ch. (2019). *Status and prospects of artificial intelligence in agriculture. Proceedings and recommendations of the national workshop on Artificial Intelligence in Agriculture* held on July 30-31, 2018 at NASC Complex, New Delhi. (Eds: Rajender Parsad, Sudeep Marwah, V. Ramasubramanian, Alka Arora, M. Balakrishnan, V.V. Sumanth Kumar, G.R.K. Murthy, S. Mohanty and D.K. Panda).

Chakrabarty, S., Shashank, P.R., Deb, C.K., Haque, M.A., Thakur, P., Kamil, D., ... & Dhillon, M.K. (2024). Deep learning-based accurate detection of insects and damage in cruciferous crops using YOLOv5. *Smart Agricultural Technology*, 9, 100663.

Das, N., Kumar, A., & Kumar, R. (2025). Drone Application and Use Cases in Smart Agriculture and Crop Surveillance: Future Research Directions. *Computer Vision in Smart Agriculture and Crop Management*, 283-302, Springer.

Department of Fisheries, Government of India. (2024). Drone initiatives in fisheries. https://dof.gov.in/drone-initiatives

Farooq, M. S., Riaz, S., Abid, A., Umer, T., & Zikria, Y. B. (2020). Role of IoT technology in agriculture: A systematic literature review. *Electronics*, 9(2), 319.

Hazarika, A., Nath, A. J., Reang, D., Pandey, R., Sileshi, G. W., & Das, A. K. (2024). Climate change vulnerability and adaptation among farmers practicing shifting agriculture in the Indian Himalayas. *Environmental and Sustainability Indicators*, 23, 100430.

Islam, S., & Rahman, M. (2022). Land fragmentation and farm size vis-à-vis sustainability at farm level in India. *Journal of Rural Studies*, 89, 1–10. https://doi.org/10.1016/j.jrurstud.2021.12.005

Kamilaris, A., Fonts, A., & Prenafeta-Boldú, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. arXiv preprint arXiv:1908.07391. https://arxiv.org/abs/1908.07391arXiv

Kulkarni, S., Kumar, V., Bhanage, V., & Gedam, S. (2023). Exploring the association between changing crop types and water scarcity: A case study over West-Central India. *Climate*, 11(5), 93. https://doi.org/10.3390/cli11050093

Kumar, V. S. (2020, October 21). CMFRI joins hands with ISRO to identify potential fishing zone. The Hindu Business Line.

MarketsandMarkets. (2024, January 29). Digital agriculture market worth $36.0 billion by 2028. PR Newswire. https://www.prnewswire.com/news-releases/digital-agriculture-market-worth-36-0-billion-by-2028---exclusive-report-by-marketsandmarkets-302046539.htmlPR Newswire

Mehta, C. R., Choudhary, V. K., & Vemireddy, V. (2023). Farm mechanization in India: Status and way forward. *Journal of Agricultural Engineering*, 60(1), 1-10.

Ministry of Finance, Government of India. (2023). Economic Survey 2022-23. https://www.indiabudget.gov.in/economicsurvey/

Mukherjee, S., Padaria, R. N., Burman, R. R., Velayudhan, P. K., Mahra, G. S., Aditya, K., ... & Bhat, A. G. (2025). Global trends in ICT-based extension and advisory services in agriculture: a bibliometric analysis. *Frontiers in Sustainable Food Systems*, 9, 1430336.

NAAS 2021. *Big Data Analytics in Agriculture*. Policy Paper No. 101, National Academy of Agricultural Sciences, New Delhi, pp16.

Parsad, R., Pradhan, U.K., Dhandapani, A. and Sharma. M. (2024). Data Science: Statistical Perspective of Data-Driven Insights. In: *Digital Literacy*: *Empowering Students with Essential Digital Tools*, Eds. Manish Sharma, Utkarsh Tripathi, Nishant Jasrotia, Sunali Mahajan. pp1-30. ISBN 978-81-979496-8-5.

Riaz, M., Yasmeen, E., Saleem, B., Hameed, M. K., Saeed Almheiri, M. T., Saeed Al Mir, R. O., ... & Gururani, M. A. Evolution of agricultural biotechnology is the paradigm shift in crop resilience and development: A review. *Frontiers in Plant Science*, 16, 1585826.

Sahoo, R. N., Rejith, R. G., Gakhar, S., Verrelst, J., Ranjan, R., Kondraju, T., ... & Chinnusamy, V. (2024). Estimation of wheat biophysical variables through UAV hyperspectral remote sensing using machine learning and radiative transfer models. Computers and Electronics in Agriculture, 221, 108942.

Singh, R. K. & Khan, A. (2023). A comparative study of quantum and classical deep learning for intelligent agriculture. *Journal of Information and Computational Science*, 13(7), 58-79.

Sizan, N. S., Layek, M. A., & Hasan, K. F. (2025). A secured triad of IoT, machine learning, and blockchain for crop forecasting in agriculture. arXiv preprint arXiv:2505.01196. https://arxiv.org/abs/2505.01196arXiv

Subeesh, A., & Mehta, C. R. (2021). Automation and digitization of agriculture using artificial intelligence and internet of things. *Artificial Intelligence in Agriculture*, 5, 278-291.

Tasgaonkar, P., & Cihan, A. (2024). How the internet of things technology improves agricultural efficiency. *Artificial Intelligence Review*. https://doi.org/10.1007/s10462-024-11046-0SpringerLink

Vanberghen, C., & Vanberghen, A. (2021). AI governance as a patchwork: The regulatory and geopolitical approach of AI at international and European level. In: *EU Internet Law in the Digital Single Market* (pp. 233-246). Cham: Springer International Publishing.

Vellingiri, A., Kokila, R., Nisha, P., Kumar, M., Chinnusamy, S., & Boopathi, S. (2025). Harnessing GPS, Sensors, and Drones to Minimize Environmental Impact: Precision Agriculture. In: *Designing Sustainable Internet of Things Solutions for Smart Industries* (pp. 77-108). IGI Global.

12 Agricultural Education

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1. Context

The agricultural sector in India emerged as a beacon of hope in spite of the recent global COVID-19 pandemic, demonstrating a 4.6% economic growth rate in the last six years, with surplus grain reserves, and employing 46.5% of workers in 2020-21 (MoF, 2024). The Government of India launched a mission on ‘Viksit Bharat @2047’ to make India a developed nation by 2047, the 100th year of India’s independence (MoE, 2023). The vision encompasses various aspects of development, including economic growth, social progress, environmental sustainability, and good governance. The term ‘*Amrit Kaal*’ denotes the time from now up to 2047, symbolizing a transformative period of immense possibilities conducive to prosperity and higher goals in India’s future. This concept is particularly significant within India’s agricultural landscape, as it stands at the nexus of socio-economic evolution and environmental imperatives.

India’s transformative agricultural journey post-independence in 1947 is legendary and widely documented (Randhawa, 1979; Paroda, 2018). Now, after over 77 years of agricultural progress, the *Amrit Kaal* marks a crucial juncture to reevaluate and strengthen agricultural education, aiming for a robust agricultural future. It demands efforts to harness the nation’s agricultural potential, bolster sustainability, and foster inclusive growth. Integrating the principles of *Amrit Kaal* into agricultural education policy and practice is imperative, equipping future generations with the requisite knowledge, skills, and mindset to navigate the complexities of modern agriculture.

This paper presents a roadmap to fortify agricultural education in India in the near and distant future. It outlines strategic imperatives and actionable

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initiatives to nurture a new generation of agriculture professionals capable of navigating modern challenges in terms of food, nutrition and environmental security.

2. Evolution of India's Agricultural Higher Education System

Numerous authors have thoroughly documented the history of Agricultural Universities (AUs) and Colleges in India (Randhawa, 1979; Sinha, 2000; Tamboli and Nene, 2013; NAAS, 2021; Agrawal *et al*., 2022; Kanpal *et al*., 2024; Pathak, 2024). Formal agricultural education began in 1877 with the establishment of the first Agricultural College in Saidapet, later relocated to Coimbatore. In some regions, agricultural education was initially integrated into engineering colleges, such as Bengal Engineering College (now Shivpur), which adopted it as part of its curriculum in 1898. The need for broader formal agricultural research and education became apparent at the dawn of the 20th century, leading to the establishment of the Imperial (later Indian) Agricultural Research Institute (IARI) in Pusa in 1905. Situated in the fertile Indo-Gangetic plains of North Bihar, Pusa was chosen for its rich agro-ecological diversity. Subsequently, colleges were established in Kanpur, Nagpur, Lyallpur, Coimbatore (1906), Pune (1907), and Sabour (1908) (NAAS, 2021).

In 1949, recognizing the need for rural-focused educational institutions, the University Grants Commission (UGC) proposed the establishment of a network of rural universities (Tamboli & Nene, 2011). Just after independence, the Indian government sought assistance from international foundations like Ford and Rockefeller to modernize agricultural practices, albeit rooted in a 'Community Development' model emphasizing village-level initiatives. In its report the expert committee proposed that support for the creation of AUs should be contingent upon adherence to fundamental principles, including: (i) independent status; (ii) co-location of agricultural, veterinary, animal husbandry, home science, technology, and science colleges on a single campus; (iii) coordination of teaching by offering courses across these institutions to facilitate a comprehensive curriculum; and (iv) amalgamation of education, research, and extension activities (Paroda, 2018).

This led to the establishment of State Agricultural Universities (SAUs) in 1960, inspired by the U.S. Land Grant University model (Agrawal *et al*., 2022). The SAUs were independently governed and focused on research and teaching. USAID's support further strengthened these institutions through partnerships with American universities (NAAS, 2021). The SAUs are directly responsible to the states, and the Governor of each state serves as the nominal head of the university and appoints a Vice Chancellor for the University. Each SAU has a dual teaching and research mandate. Funds for research come from state governments, the central government through the Indian Council for Agricultural Research (ICAR), and other sources such as foundations and the private sector.

Postgraduate (PG) agricultural education in India took root in the 1920s with the authorisation of IARI to offer advanced courses in agriculture (Agrawal *et al*., 2022). This initiated a deep and enduring connection between India's agricultural research and educational institutions (Tamboli and Nene, 2013). By 1958, IARI attained university status, evolving into the National Postgraduate School of Agriculture, thereby expanding its offerings to encompass M.Sc. and Ph.D. degrees across various agricultural disciplines. Unlike the traditional Indian approach of awarding a Ph.D. solely based on dissertations and oral examinations, IARI introduced structured courses for graduate students. A significant contribution of IARI was its role in training a substantial number of Ph.D. scholars to populate the SAUs established in the 1960s. This training emphasized a blend of coursework and field research (NAAS, 2021).

3. Agricultural Universities as Catalysts of India's Progress

Since the time of the independence of India, AUs in conjunction with ICAR institutes have been instrumental in the cultivation of top-tier human capital by coordinating, supporting, and guiding various facets of agricultural higher education (AHE). The creation of trained, quality human resources in the agriculture and allied sectors through the establishment of AUs was pivotal in the ushering in of the green revolution, followed by the white, yellow, blue, and rainbow revolutions. This concerted effort of cultivating essential scientific expertise, nurturing educators, advancing technologies, and facilitating their dissemination has propelled India from a state of dependency on external food sources to achieving the fundamental right to food security (NAAS, 2021).

The Green Revolution has been instrumental in elevating food production to unprecedented levels through adopting high-yielding varieties and efficient input management, particularly in cultivating staple crops like wheat and rice. Over the years, the impact of the Green Revolution has been vividly reflected in the substantial increase in crop yields, as evidenced by the rise in productivity from 0.7 tons per hectare in 1970 to an impressive 2.4 tons per hectare by the year 2024, with a total food production of 332.5 Mt. Importantly, this surge in productivity occurred while maintaining a relatively constant net sown area. Similarly, a ten-fold increase in milk production occurred from 21.2 Mt (1968) to 221.1 Mt (2022). The increase in milk production is driven by technology, not by a larger animal population. Today, India is the third-largest fish-producing country with around an 8% share in global fish production. The Golden Revolution in horticulture can be gauged by an almost 14-fold jump from 25 Mt (1950-51) to ~350 Mt (2022-23). Mechanization has greatly removed drudgery for Indian farmers, and today India is the largest producer of tractors globally (>one million) (Pathak, 2024).

4. India's Current AHE Landscape

At present, India boasts the world's third largest higher education system, comprising 1,074 universities, 139 other autonomous institutes/body (e.g. Indian Institute of Technology, All India Institute of Medical Sciences, Indian Institute of Management, National Institute of Technology, Indian Institute of Sciences Education and Research etc.) and ~42,000 colleges offering a diverse range of programs (AISHE, 2022; UGC, 2023, Table 1). This three-tiered structure, consisting of universities, colleges, and affiliated courses, is overseen by the Ministry of Education and regulated by the UGC to ensure adherence to national standards. A distinguishing feature

Table 1. Total general and agricultural universities in India.

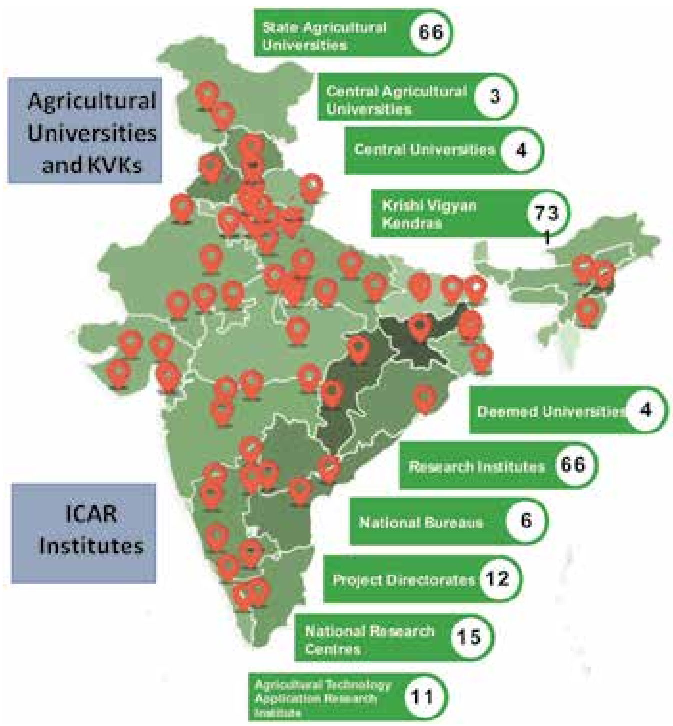
Type of University	Total no.	Universities imparting education in agriculture and allied subjects (AUs)	AU (%) of total
State University	460	66	14.3
Deemed-to-be-University	128	5	3.9
Central University	56	7	12.5
Private University	430	179	41.6
Other autonomous institutes/bodies (IIT, AIIMS, IIM, NIT, IISER etc.)	139	0	0.0
TOTAL	**1,213**	**257**	**21.2**

Source: *UGC (2023); ICAR (2024)*

of this system is its reliance on public funding, making it accessible to a vast student population.

In the realm of agriculture and allied subjects, 257 universities in India are granting degrees, both in the public (79) and private sectors (179). Operating within the framework of the government supported National Agriculture Research, Education, and Extension System (NAREES), there are currently 66 State Agricultural Universities (SAUs), 4 Deemed-to-be-Universities (DUs), 3 Central Agricultural Universities (CAUs), and 4 Central Universities (CUs) equipped with agricultural faculties (Agrawal and Jaggi, 2024). Thus, out of the total universities and Institutes in India, 21.1% offer degrees in agriculture and allied subjects. In addition, all the 114 ICAR institutes comprising four DUs (IARI, IVRI, NDRI and CIFE), 66 national institutes, six national bureaus, 12 project directorates, 15 National Research Centers, and 11 Agricultural Technology Application Research Institute (ATARIs), along with the 731 Krishi Vigyan Kendras (KVK) contribute directly/indirectly in the agricultural education and training ecosystem of the country (Fig. 1). Beyond academic pursuits, these

Figure 1. *Network of Research, Education and Extension Institutes of the NAREES.*



establishments play a pivotal role in agricultural research and knowledge dissemination to farmers and other stakeholders.

Administratively, the DUs and CAUs are governed by the ICAR under Department of Agriculture Research and Education (DARE). The CUs come under the regulations of UGC, and SAUs are governed by the statutes of the respective state departments. While agricultural education falls under the jurisdiction of state subjects, the ICAR offers financial assistance to SAUs, DUs, CAUs through development grants and merit-based scholarships/fellowships (Agrawal and Jaggi, 2024). The Agricultural Education Division (AED) within the ICAR serves as the operational branch responsible for overseeing all educational initiatives (Agrawal *et al*., 2022). Its mandate includes: (i) strategic planning, promotion, and coordination of agricultural education nationwide; (ii) enhancement of the quality and relevance of higher agricultural education; and (iii) reinforcement of the agricultural university system to cultivate proficient human resources in agriculture and related fields (Agrawal and Jaggi, 2024). The development grants from ICAR are designated to support various aspects, including the upkeep of teaching facilities and materials, facilitating PG research, enhancing faculty capabilities, and ensuring efficient administration of admissions and practical training. Consequently, the ICAR holds a mandate equivalent to that of the UGC in coordinating agricultural education activities and overseeing federal funding and monitoring initiatives in this domain (Paroda, 2018). Over the years, human capital cultivated by the agricultural education system has played a crucial role in the evolution of the agricultural sector (Paroda, 2018; Singh *et al*., 2022).

The private-funded universities are growing rapidly in the country, and are mostly multidisciplinary in nature. Out of the total 179 recognized private universities by UGC, 14 DUs and 167 universities offer courses in agriculture and allied subjects (ICAR, 2024). Overall, public and private institutions offer many programs from diploma, undergraduate (UG) to doctoral levels, encompassing domains like agriculture, horticulture, animal husbandry, fisheries, veterinary sciences, agricultural engineering, forestry, community science, food nutrition and dietetics, food science and technology, sericulture, plant and animal biotechnology, diary technology, agribusiness management, natural farming and more (Agrawal *et al*., 2022; Agrawal and Jaggi, 2024). Agriculture stands at the top choice (~45%) of students, followed by Veterinary, Horticulture, Engineering, etc. (ICAR-NAHEP, 2023).

Overall, publicly funded AUs constitute a relatively modest proportion (9%) of all universities in the higher education landscape. In terms of faculty strength, each AU employs anywhere from fewer than 100 to over 600 faculty members, with an average of 309 faculty members per AU, supported by an annual average budget of Rs 235 crores (ICAR-NAHEP, 2023). The student enrolment reveals a narrower footprint, amounting to less than 1% of the total enrolment in higher education (ICAR-NAHEP, 2023). The current aggregate student population within public-funded AUs stands at about 50,000, with 30,000 pursuing UG degrees, 15,000 PG programs, and 5,000 engaged in doctoral studies and about 45,000 students enrolled in private institutions (ICAR-NAHEP, 2023). These statistics underscore the specialized nature of agricultural education, emphasizing the need for targeted efforts to expand both the reach and impact of AUs in the broader educational landscape.

5. National Education Policy (NEP) 2020

The introduction of the National Education Policy (NEP) 2020 by the Government of India has heralded a profound shift in the educational paradigm of the nation (MoE, 2024). Recognizing the evolving needs of a rapidly changing world, the policy emphasizes the imperative to launch comprehensive reforms across all levels of education. Before the implementation of the NEP in 2020, the last major alteration to India's education policy occurred with the introduction of the National Policy on Education (NPE) in 1986 and its subsequent modification in 1992. These policies provided a framework for educational development in India for several decades before the NEP 2020 brought about significant reforms and updates to the education system (MoE, 2024).

With a focus on promoting holistic development, fostering critical thinking, and nurturing creativity, the NEP 2020 advocates for a learner-centric approach that encourages flexibility and choice. Furthermore, it underscores the importance of bridging existing gaps in access, equity, and quality, thereby ensuring inclusive and equitable educational opportunities for all. Through its innovative vision and forward-thinking strategies, the NEP 2020 seeks to transform India's educational ecosystem, equipping learners with the skills and knowledge needed to thrive in the 21st century (MoE, 2024). The NEP 2020 proposed several key changes to the existing higher education institutes (HEIs), encompassing agricultural education along with major milestones and broad timelines (Box 1).

Box 1. Major Recommendations of NEP 2020

- Transitioning towards **multidisciplinary universities and colleges**, ensuring at least one institution in or near every district, and expanding the number of Higher Education Institutions (HEIs) across India offering instruction in local/Indian languages.
- Advancing towards a more **multidisciplinary undergraduate education**.
- Progressing towards **greater faculty and institutional autonomy**.
- Overhauling **curriculum, pedagogy, assessment, and student support** to enrich student experiences.
- Reinforcing the **integrity of faculty and institutional leadership** positions through **merit-based appointments** and career advancement based on teaching, research, and service.
- Establishing a **National Research Foundation** to finance exemplary peer-reviewed research conducted by universities and colleges.
- Instituting **governance** of HEIs by highly qualified **independent boards** with academic and administrative autonomy.
- Implementing "**light but tight**" regulation through a single regulator for higher education.
- Enhancing **access, equity,** and **inclusion** through various measures, including increased opportunities for exceptional public education, scholarships provided by private/philanthropic universities for **disadvantaged and underprivileged students**, online education, Open Distance Learning (ODL), and ensuring that all infrastructure and learning materials are accessible to **learners with disabilities**.

Accordingly, ICAR has developed a roadmap entitled 'Implementation Strategy for National Education Policy-2020 in Agricultural Education System', which outlines the overarching measures that ICAR would undertake to implement the NEP in NAREES (Box 2).

Thus, NEP 2020 calls for institutions offering professional (single subject) or general agriculture education to organically evolve into institutions/ clusters offering both, seamlessly by 2030, that means convert into multidisciplinary research-intensive institutions while continuing focus on agriculture. The design of agricultural education will have to be strengthened

Box 2. Overarching Domains of Focus for Implementation of NEP 2020 in the NAREES by ICAR

1. Restructuring of AUS

- Consolidating AHE by transforming AUs/Colleges into larger multidisciplinary institutions, each accommodating 3,000 or more students. This transformation will expand academic programs to include basic sciences, social sciences, and allied disciplines alongside agricultural sciences, transitioning single-stream universities into multidisciplinary institutions by 2030 while maintaining a focus on agriculture.
- Currently numerous affiliating colleges operate, both in public and private sector. NEP-2020 mandates bringing them under new higher education norms, aiming to abolish the affiliation system by 2035 through collaborative efforts with universities.
- Utilizing existing expertise and resources, ICAR DUs will undergo transformation into multidisciplinary, research-intensive institutions, leveraging their strengths to enhance their educational and research capacities.

2. Academic Restructuring of AHE

- Restructuring academic programs to offer multiple entry and exit points, allowing students to earn certificates, diplomas, undergraduate degrees, or engage in research, along with one or two-year Master's programs. Residential requirements for UG and PG programs to be relaxed to facilitate seamless transitions for students.
- A Deans' Committee to revamp UG curricula in line with NEP guidelines. Universities may adjust UG intake to ensure that students exiting with certificates or diplomas do not affect overall degree numbers. AUs granted time until 2025 to implement the restructured four-year UG program, alongside separate criteria for one-year certificates and two-year diplomas in Agriculture.
- PG programs to adopt a multidisciplinary approach, allowing students to choose majors and minors. Teaching assistantships to be encouraged for PhD students to address faculty shortages.
- Boost Gross Enrolment Ratio (GER) in AUs by increasing seats by at least 10% annually from the 2021-22 academic session. Scores from the common entrance test conducted by ICAR to be utilized for admissions across all AUs for UG, PG, and PhD programs. UG entrance exams may be conducted in regional languages, aligning with directives on Academic Bank of Credits (ABC).

Contd...

3. Role of ICAR in Regulation of AHE

- Empowering ICAR as a Professional Standard Setting Body (PSSB) for AHE, tasked with developing curricula and academic standards nationwide. Through its role in the proposed General Education Council (GEC), ICAR to ensure uniformity in agricultural education across public and private institutions. As a GEC member, ICAR will participate in regulating agricultural education under the National Higher Education Regulatory Council (NHERC), the primary segment of the proposed Higher Education Commission of India (HECI).
- Establishment of National Accreditation Council (NAC) as a meta accrediting body, assigning accreditation duties to select institutions. ICAR's NAEAB may be designated as an accreditor for universities and colleges offering agricultural education.
- To promote 'internationalization at home,' an International Students Office to be established to support and attract international students. Collaborations, exchanges, and MoUs with foreign institutions will enhance global standards and opportunities.
- In light of evolving educational methods, traditional approaches to be supplemented with e-learning platforms like SWAYAM, DIKSHA, and SWAYAMPRABHA. Utilizing tools such as two-way video and audio interfaces will enhance online teaching, especially amid the current pandemic and for global outreach.

Source: *ICAR (2021)*

towards developing professionals with the ability to understand and use local knowledge, traditional knowledge and emerging technologies, while being cognizant of critical issues of declining profitability and/or productivity but enhanced economic aspirations of farmers, climate change, food sufficiency and benefiting the local communities directly.

The existing institutions will need to reinvent themselves and their structure will undergo an evolution of sorts while being provided with adequate funding, legislative enablement and autonomy in a phased manner. The universities, in turn, will need to display commitment to institutional excellence, engagement with their local communities and accountability. As envisaged in NEP-2020, each AU/AHE institution should prepare a Strategic Institutional Development Plan (SIDP) that contains specific action plans for increasing participation from Socio–Economically Disadvantaged Groups (SEDGs). AUs will plan their phased growth initiatives, assess their own progress, and reach the goals set in the SIDP. The SIDP will thus be an important parameter for accessing more funding and achieving higher rankings (MoE, 2024).

6. Recent Initiatives of ICAR for Strengthening AHE

With changing policy (e.g., NEP 2020) and to keep pace with the rapidly evolving knowledge, innovations, and technologies in agriculture, ICAR has taken periodic initiatives as a commitment to enhancing the quality of agricultural education, as enumerated below.

6.1. Reforming the admission process

In 2020-21, ICAR adopted the Common University Entrance Test (CUET), administered by the National Testing Agency (NTA), for 12 UG courses in agriculture and allied sciences, broadening admission avenues for these programs (Agrawal and Jaggi, 2024). This initiative enables students vying for the prestigious 20% All India Quota (AIQ) seats in esteemed institutions like Rani Laxmi Bai CAU, Jhansi; Dr Rajendra Prasad CAU, Pusa; ICAR-National Dairy Research Institute (NDRI) and ICAR-IARI, New Delhi, to pursue their academic endeavors through CUET (UG). Consequently, there has been a seven-fold surge in registrations compared to the previous years.

The All-India Entrance Examination for admission (AIEEA) to M.Sc. in 80 disciplines and the All-India Competitive Examination (AICE) for admission to Ph.D. degree programs continue to be vital components of ICAR's efforts to enhance agricultural education (Agrawal *et al.*, 2022). Moreover, an increase to 30% in AIQ seats for PG and PhD programs opened avenues for advanced agricultural education. The number of UG seats has risen from 4,285 (2022-23) to 4,800 (2023-24). The total number of applicants surged from 0.9 lakhs (2022–23) to 5.3 lakhs (2023–24), indicating a 5.5-fold increase per seat, with 110 applicants per seat. The proportion of female students rose from 26% in 2017 to 49% in 2023 (ICAR-NAHEP, 2023).

To diversify agricultural education and mitigate insular tendencies, students are actively encouraged to pursue higher studies in other states. This encouragement takes the form of National Talent Scholarships, Junior Research Fellowships (JRF), and Senior Research Fellowships (SRF) for PG and doctoral admissions. Additionally, new fellowships from the Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC) and the Association of Southeast Asian Nations

(ASEAN) offer opportunities for students from member states to pursue PG and doctoral studies in Indian agricultural universities (Agrawal *et al*., 2022).

6.2. Entrepreneurship

The Student READY (Rural Entrepreneurship Awareness Development Yojana) initiative was introduced by the Hon'ble Prime Minister of India in 2015 to cultivate agri-entrepreneurs. It spans a full year within the final year of the UG program in various agricultural and allied sciences, endorsed by the fifth Dean's Committee (Agrawal *et al*., 2022). The program aims to nurture young agri-preneurs equipped for modern, knowledge-intensive agriculture. It encompasses activities focusing on project development, decision-making, team coordination, accounting, quality control, marketing, and conflict resolution (Agrawal *et al*., 2022).

Part of the Student READY initiative, the Rural Agricultural Work Experience (RAWE) program empowers young agri-graduates with practical experience, community engagement skills, and extension resources (Agrawal and Jaggi, 2024). This enables them to effectively disseminate the latest agricultural advancements to farmers. Through hands-on training in rural settings, students gain insights into extension services, rural development initiatives, and diagnostic techniques relevant to real-world agricultural challenges. The RAWE program is undergoing enhancements to improve its effectiveness, including the establishment of a digital platform for streamlined reporting, monitoring, and data analysis (Agrawal and Jaggi, 2024). This ensures that graduates return with enhanced knowledge, empathy, and innovative solutions, contributing to sustainable agricultural growth.

6.3. Dynamic course curricula

The ICAR has been implementing periodic reforms to uphold the standard of agricultural education. This involves the establishment of Deans' Committees, which engage in consultations and discussions with stakeholders to revise academic norms and standards in response to emerging challenges and opportunities. This Committee provides recommendations about the curricula, course contents, degree nomenclature, and reforms in admission and examination, pedagogy, faculty requirement, governance, etc. Currently, the focus of the '6th Deans Committee' is on restructuring UG course curricula to align with the NEP 2020. This initiative aims to integrate vocational courses, enhance skill development, and usher in a new era in agricultural education (Agrawal and Jaggi, 2024).

ICAR has also been responsible for the Professional Standard Setting Body (PSSB) under the NEP-2020. This body will give recommendations on restructuring of UG programs across AUs to integrate more practical and applied components, establishment of a one-year Certificate course framework with specific subject areas and assessment criteria leading to a two-year Diploma program, and the development of admission criteria considering the flexibility for multiple entry and exit. Additionally, guidance will be provided on fostering entrepreneurship among students, devising strategies to incrementally boost the gross enrollment ratio (GER) in AUs, ensuring clarity in defining UG and PG degrees to meet both general market demands and specialized job requirements while maintaining consistency in degree nomenclature

Starting from the 2021-22 academic session, the revised syllabus, incorporating cutting-edge courses recommended by the 'Broad Subject Matter in Agriculture (BSMA)' committee, has been implemented for PG and doctoral programs spanning 79 disciplines. These courses cover topics such as genomics, nanotechnology, precision farming, conservation agriculture, and others (Agrawal and Jaggi, 2024).

Additionally, non-credit courses on personality development, leadership, yoga, life skills, and ethics have been included in the curriculum. In a move to promote sustainable agricultural practices, ICAR has introduced natural farming into both UG and PG academic curricula. Approximately 200 faculty members from agricultural universities have undergone training in various aspects of natural farming (Agrawal and Jaggi, 2024). Experiential learning units for natural farming have been established in AUs, and four AUs have admitted 45 students for the 2023–2024 academic year to pursue a B.Sc. (Hons.) in Natural Farming.

6.4. Vocational skills development

In accordance with the directives outlined in the National Skill Development Framework and NEP 2020, universities are diversifying their academic curricula to include vocational courses, in an endeavor to address the evolving needs of the job market and to create avenues for non-farm employment. Approximately 200 new vocational courses have been introduced across AUs to augment students' skill sets (Agrawal and Jaggi, 2024). Furthermore, there is a concerted effort to establish agribusiness incubation centers at each university to support startups in agriculture and allied sectors, thereby fostering entrepreneurship. Special attention is given to enhancing students' problem-solving, creative thinking, and communication abilities, which are deemed crucial for catalyzing transformative changes in the agricultural domain. Universities are encouraged to initiate mentoring schemes, establish startup incubation centers, and implement entrepreneurship development programs to aid students and budding innovators in translating their concepts into successful business ventures (Agrawal and Jaggi, 2024).

6.5. Accreditation for quality assurance

Initially, the UGC oversaw the assessment and accreditation of AHE. However, in 1965, this responsibility shifted to ICAR. Following a reorganization in 1973-74, the Standing Committee on Agricultural Education was replaced by the Norms and Accreditation Committee (NAC) in 1974, tasked with setting norms for accrediting AUs. In 1996, ICAR established the National Agricultural Education Accreditation Board (NAEAB) with clear guidelines to enhance and maintain the quality of agricultural education. Currently, NAEAB manages this task and has devised guidelines to ensure a more objective accreditation process. Moreover, the entire accreditation documentation process has transitioned online through a dedicated portal, facilitating efficiency (https://accreditation.icar.gov.in/). Efforts are underway to further streamline and simplify the accreditation process by minimizing time gaps between activities.

ICAR's Model Act, initiated in 1966 and subsequently updated, serves as a comprehensive legal framework guiding the implementation of regulations across India's states, promoting uniformity in agricultural education and research. In its pursuit of excellence, ICAR has continually revised the Model Act to address evolving needs, rectify inconsistencies in existing university acts, and bolster provisions ensuring unparalleled quality in agricultural and allied sciences disciplines (ICAR, 2023).

6.6. AUs ascent in national institutional ranking framework (NIRF)

University rankings have gained crucial importance in today's increasingly globalized world, where education is becoming more internationalized. They serve as vital tools for making well-informed decisions about university choices, offering a broad spectrum of information on excellence indicators. The recent inclusion of agriculture and allied sectors in the prestigious National Institutional Ranking Framework (NIRF) represents a significant milestone in this regard. NIRF's parameters are categorized into five main areas: Outreach and Inclusivity, Teaching, Learning, and Resources, Research, Professional Practice, Collaborative Performance, Perception, and Graduation Outcomes.

Released on June 5, 2023, the NIRF list encompasses the rankings of 40 AUs within the 'Agriculture and Allied Sectors' category (https://www.nirfindia.org/OverallRanking.html). Notably, ICAR's four Deemed Universities, namely the Indian Agricultural Research Institute (IARI) in New Delhi, National Dairy Research Institute (NDRI) in Karnal, the Indian Veterinary Research Institute (IVRI) in Izatnagar, and the Central Institute of Fisheries Education (CIFE) in Mumbai, have secured positions within the top 10. These accolades testify to their steadfast commitment to academic excellence and innovative approaches in their respective fields.

6.7. Embracing collaborations

To prepare students for success in a competitive global landscape, there's a concerted effort to foster partnerships between academia and industry in agricultural education (Soam *et al*., 2023). These collaborations with prominent agricultural firms provide students with hands-on experience, exposure to cutting-edge research, and opportunities for internships and practical projects. By nurturing these industry-institute alliances, students are better prepared for the challenges of the global arena. ICAR has been actively initiating partnerships with various organizations to bolster its educational and related endeavors (Soam *et al*., 2023).

6.8. Infusing agricultural studies into the school curriculum

Recognising the paramount importance of agriculture in the Indian context, the ICAR has taken a significant stride towards integrating the agricultural curriculum into school education. A thought-provoking brainstorming session on Mainstreaming Agricultural Curriculum in School Education (MACE) was convened in 2022, drawing participation from school principals, senior educators, and experts, including representatives from ICAR, the Central Board of Secondary Education (CBSE), and the National Council of Educational Research and Training (NCERT). Throughout various sessions, attendees delved into the necessity and methods of introducing agriculture as a subject in school curricula. As a tangible outcome of MACE, collaborative efforts are now underway with the CBSE to infuse agricultural concepts and principles into the existing syllabi. Further, initiatives have been made to introduce agriculture as an activity-based subject for middle school, especially for their 'bag-less days'. These proactive initiatives aim to spark students' interest in agriculture from an early age and instill a profound appreciation for its indispensable role in our lives.

7. NAHEP-A Gamechanger in India's AHE Landscape

The ICAR initiated the National Agricultural Higher Education Project (NAHEP) in collaboration with the World Bank (WB) in November 2017 and culminates on September 30, 2024. Sanctioned for USD 165 million (Rs 1,100 crore at the 2017 conversion rate) on a 50:50 cost basis between the WB and the Government of India, this mega-program was conceived with the primary objective of enhancing the quality and relevance of education provided by participating AUs and ICAR institutes, thereby boosting agricultural productivity and elevating the standards of higher education (Box 3).

7.1. NAHEP beneficiaries and outcomes

NAHEP focused on infrastructure development, faculty and student support, governance enhancements within AUs, raising educational standards and emphasizing job creation. The project also aimed to create

Box 3. Broad Objectives of NAHEP

1. Quality Enhancement

AUs propose and implement technically sound and verifiable investments, in (i) Institutional Development Plans (IDPs), (ii) Centers for Advanced Agricultural Science and Technology (CAAST) and (iii) Innovation Grants (IG). These components focused to enhance the faculty-student learning environment, improve the learning outcomes and make students more employable.

2. Relevance Improvement

Relevance is ensured through greater alignment of academic curricula and course content with the skill sets being demanded in the agriculture and allied services sector, and expanded certificate-level vocational courses to fill the gap for trained technical personnel, especially in market-led extension. The overall approach is to meet the demand in the market by re-orienting the skill sets at AUs, especially in agricultural higher education and avoid a misfit situation.

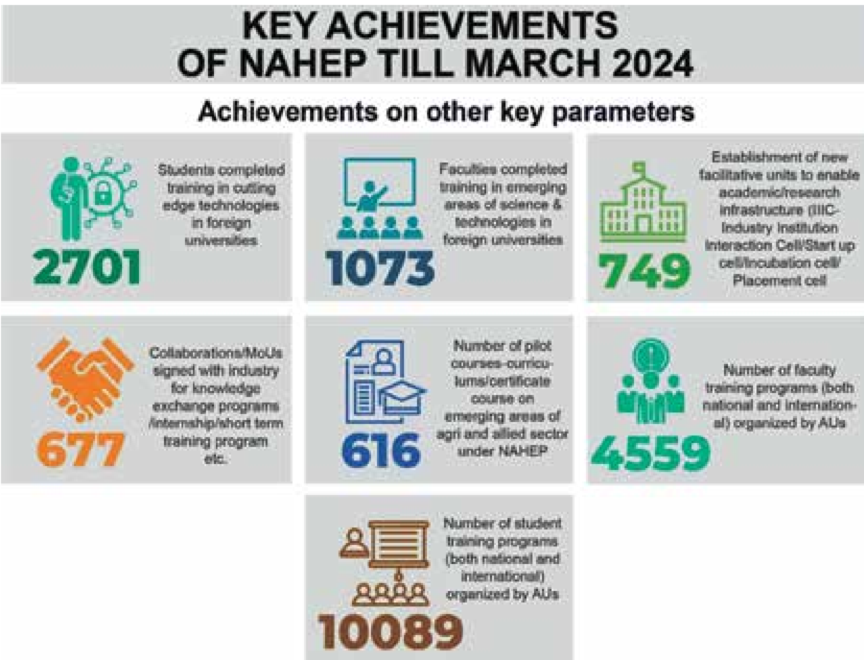
3. Cumulative Augmentation of Quality & Relevance

Both quality and relevance are augmented through investments in ICAR that improve its ability to set and enforce standards across the ICAR-AU System and build international cooperation to the benefit of agricultural higher education across the nation.

an enabling research and innovation-led entrepreneurship ecosystem at par with global standards. Under NAHEP, the landscape of AUs has undergone significant evolution, benefiting 77 institutions within the ICAR-AU System. These included 62 AUs (22 under IDP, 16 under CAAST, and 24 under IG). Furthermore, three ICAR institutes, namely, ICAR-Indian Agricultural Statistics Research Institute (IASRI), New Delhi, ICAR-National Academy of Agricultural Research Management (NAARM), Hyderabad and ICAR-National Institute of Agricultural Economic and Policy Research (NAIP), New Delhi, actively implemented Component 2 of NAHEP on 'Investment in ICAR Leadership in Agricultural Higher Education'.

Through integration, transformation, and inclusion, NAHEP uplifted AUs, improving education quality and relevance and exceeding expectations across various metrics (Box 4 and Fig. 2). In the 2016-17 academic year, the placement rate stood at 41.9%. While the anticipated placement rate for March 2024 was 48.1%, the universities surpassed this projection by nearly 30%, achieving a remarkable placement rate of 61%. Over 2,700 students and 1,000 faculty received international training, boosting skills and perspectives. Importantly, the average h-index per AU increased

Figure 2. *Some quantitative outputs achieved under NAHEP.*



For details see - https://nahep.icar.gov.in/

Box 4. A Few Qualitative Outputs Achieved under NAHEP for Improving Quality and Relevance of AHE

Area of benefit	Output	Outcome expected
Capacity strengthening of faculty and staff	Professional development programs, workshops, and training sessions held for faculty and staff to update their knowledge and teaching methodologies.	Collaborations with international agri-institutions for teaching and research
Linkages with the global knowledge economy	Established partnerships with global agricultural research institutes, universities, and industry leaders to exchange knowledge, technology, and best practices.	Joint research projects, student exchanges, and faculty visits
International Experiential Learning	Opportunities for students to gain international exposure through exchange programs, internships, or study abroad experiences.	With broadened perspectives, students equipped with different agricultural practices and skills in a global context would have better career opportunities.
Learning-centered education	Acquired innovative teaching methods that prioritize active learning, problem-solving, and practical application of knowledge.	Would facilitate curriculum reforms, the integration of technology in teaching, and the development of experiential learning opportunities within the curriculum.
Partnership with private industries	Collaborated with private agricultural companies and industries to provide students with hands-on training, research opportunities, and access to state-of-the-art facilities.	Partnership could facilitate industry-relevant curriculum development and joint research projects that address real-world challenges.

For details see - https://nahep.icar.gov.in/

from 27 to 34, with top AUs like IARI, PAU, CCSHAU, and IVRI leading in research impact. On-time graduation rates reached 95.7%.

7.2. Digital initiatives under NAHEP

In the framework of Component 2 and the subproject on 'Resilient Agricultural Education System (https://nahep2.icar.gov.in/). It comprised a robust three-tier digital framework aimed at bolstering digital infrastructure, enhancing digital capabilities, and delivering relevant digital content for widespread adoption. Leveraging information and communication technology (ICT), it has facilitated blended and flipped learning approaches, fostering closer collaboration with industry and government to create a more market-oriented teaching and learning environment. State-of-the-art digital infrastructure, featuring advanced amenities such as smart boards, projection systems, and video conferencing facilities, was established. Prominent digital initiatives like the 'E-Learning Portal,' 'Agri-DIKSHA,' 'Virtual Reality Experience Labs, setting up AR/VR labs and 'Academic Management System' have been introduced to enrich the learning journey in 75 AUs. A recent addition, the 'Blended Learning Platform' (BLP)equips learners and administrators with tools for enhanced knowledge retention, engagement, and collaboration, aligning seamlessly with the vision outlined in NEP-2020 for a hybrid learning ecosystem. Additionally, over 60 SCORM-compliant e-courses on agriculture have been developed under RAES. Various sensitization workshops were conducted for Vice Chancellors, Deans, Directors, and BLP nodal points to facilitate capacity building and knowledge transfer.

Overall, more than 5 lakh students and faculty, including 45% women, have been direct beneficiaries of NAHEP in the last 6 years. NAHEP has catalyzed the evolution of AUs by promoting digitalization, innovation, and collaboration, thereby equipping them to meet the dynamic challenges of the agricultural sector and contribute meaningfully to its advancement.

7.3. NAHEP study on 'human resource requirement in agriculture'

In 2023, a study named 'Human Resource Requirement in Agriculture' was carried out by ICAR under NAHEP to assess the needs for the next twenty years (Tripathi *et al*., 2023). The study aimed to assess both current resource capacity and efficiency, as well as future needs. Salient findings of the study are given in Box 5. Only 20% of students reported getting placed immediately after passing out, whereas 10% mentioned they got placed after a 1 to 5-year gap. About 50% of graduates from Agriculture, Biotechnology, Food Technology, Nutrition and Dietetics, Sericulture and Veterinary informed that they got placed without institute support

Box 5. Human Resource Requirement in Agriculture

1. Skill Development

About 50% of students stated that their current educational programs equipped them with crucial skills, including personality development, in-depth subject knowledge, effective communication, research abilities, and familiarity with industry norms and behaviors.

2. Career Aspirations

Half of these students aspire to become agricultural officers, prepare for competitive exams, pursue higher studies, or venture into entrepreneurship.

3. Faculty Viewpoints

Faculty members highlight an increasing focus on opportunities within the private sector and stress the significance of skill sets that go beyond academic coursework.

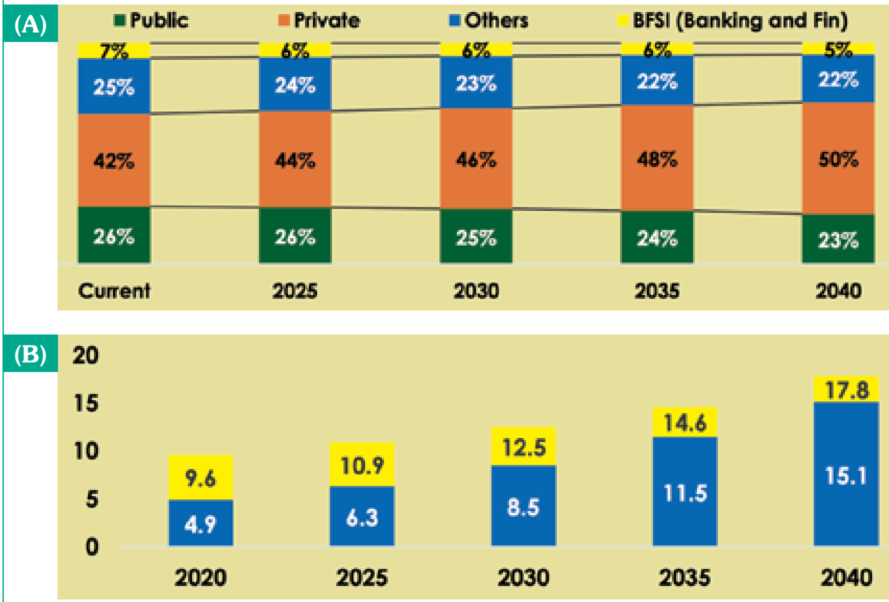
Graduate Employment

Only 23% of graduates secured jobs immediately after graduation. However, 50% of specialized graduates, particularly in Agricultural Biotechnology and similar fields, successfully found jobs independently.

immediately after academics. The study underscores the significance of a comprehensive education surpassing traditional academics. It emphasizes the urgency for skill development aligned with evolving job market demands, encompassing soft skills and entrepreneurial capabilities.

The study also revealed a substantial gap between the supply and demand of human resources in India's agriculture and allied sectors (Fig. 3). Presently, while the demand for agriculture and allied graduates stands at about 9.6 lakhs, only 4.9 lakh graduates are available, leading to a 49% shortfall. However, there's a positive side as this difference is expected to gradually decrease in the upcoming decades, falling to 43% by 2025, 32% by 2030, 22% by 2035, and further down to 15% by 2040. These numbers highlight the crucial need to adjust agricultural education to meet industry needs. Employers require a workforce equipped not only with technical knowledge but also with critical thinking, problem-solving, and entrepreneurial abilities. By tailoring education to the specific skills and knowledge required in the sector, graduates can be better prepared to fill current and future job openings, thus reducing the gap between supply and demand. Based on this study, short-, medium- and long-term strategies have been proposed (Tripathi *et al*., 2023):

Figure 3. (A) *Sectoral level human resource requirement up to 2040;* ***(B)*** *Supply and demand gap estimations (figures in lakhs)*



Source: *Tripathi et al., 2023*

7.3.1. Short-term strategies (by 2030)

- Attract students through innovative promotional methods beyond traditional advertising, particularly at the school level.
- Regularly update the curriculum to maintain market relevance alongside enhancing faculty competencies.
- Establish 552 additional educational institutions covering diverse disciplines like Agriculture, Veterinary Science, Horticulture, and Agricultural Engineering.
- Utilize EdTech, especially in rural areas.
- Transition specialized agricultural universities to a multidisciplinary model, fostering problem-based learning and diverse skill development.

7.3.2. Medium to long-term strategies (by 2040 and beyond)

- Elevate 20 agricultural universities to the top 100 QS World University Rankings.
- Enhance the employability of the agricultural university students.

8. Reimagining Agricultural Education in India

The experience with NAHEP has provided many leads for further elevating agricultural education in India through a comprehensive strategy. Here are several crucial areas for enhancement:

8.1. Modern curriculum for modern challenges

Regularly update the curriculum to reflect current industry needs and advancements in areas like precision agriculture, biotechnology, and IoT-enabled agriculture. Sustainable farming practices, data analysis, and the use of digital tools like remote sensing and automation should be seamlessly integrated into the course curricula in all AUs. The challenge posed by climate change calls for adaptive strategies and sustainable agricultural practices, which should be integrated into educational frameworks. Moreover, emerging trends like vertical farming and agroecology require a forward-looking curriculum, equipping students to seize new opportunities and innovate in evolving agricultural contexts. It's crucial that the curriculum addresses sector-specific challenges, such as those in legumes and oilseeds, while also integrating research in areas like space agriculture. With space agencies exploring crop cultivation beyond Earth, a dynamic curriculum is essential to keep students updated on the latest developments.

8.2. Changes in curriculum review process

Curricula are reviewed and revised every decade, with input from stakeholders, including faculty, but final decisions lie with the Deans' Committee. Reviewing these twice a decade may now be prudent, ensuring responsiveness to changing needs. Universities may be given autonomy to adjust their curricula based on regional, market, and student requirements. The Deans' Committee review process should include representation from students, faculty, government, and industry.

8.3. Skilling beyond the classroom

There is a growing emphasis on cultivating critical thinking, problem-solving skills, and adaptability among students to address the complex challenges facing the agriculture sector. This would call for moving beyond rote learning and traditional theoretical approaches. The way forward is to integrate soft skills development into the curriculum, focusing on communication, teamwork, and leadership. Encourage practical learning experiences through farm internships and industry collaborations to bridge the theoretical-practical gap.

8.4. Harnessing technology for learning

Teaching methods should be restructured, incorporating emerging technologies, fostering interdisciplinary approaches, and integrating real-world experiences into the learning process. Utilizing educational technology (EdTech) tools to enhance learning and accessibility, particularly in remote rural areas, is imperative. Online courses, virtual labs, and mobile applications can play a vital role in knowledge dissemination and cater to diverse learning styles.

8.5. Fostering innovation and entrepreneurship

Encourage a culture of innovation and entrepreneurship among students. Research into new technologies and sustainable practices that address challenges faced by Indian agriculture is crucial. This can involve establishing incubation centers and providing resources for student-led startups within the agricultural sector.

8.6. Building bridges between academia and industry

Strengthen the connection between agricultural universities and industry stakeholders. Collaborative research projects, guest lectures by industry experts, and internship programs can provide students with invaluable real-world experience and prepare them for the demands of the job market. This holistic approach aims to equip future agricultural professionals with the knowledge, skills, and mindset necessary to thrive in a rapidly evolving global landscape.

9. Shared Vision for Agricultural Universities @2047

By 2047, Indian AUs should aim to position themselves as prime destinations for agricultural education, research, and innovation on the global stage. Envisioned as pivotal agents of change, they are poised to spearhead a revolution in sustainable agricultural practices, bolstering food security, promoting net-zero emissions, fostering rural prosperity, and setting the stage for multidisciplinary education. This collective ambition encompasses the following broad areas that need to be addressed:

Excellence in education: Indian AUs will offer cutting-edge educational programs that foster critical thinking, creativity, and problem-solving skills among students. These programs will be designed to meet the evolving needs of the agricultural sector, incorporating interdisciplinary approaches and experiential learning opportunities.

***Leading-edge research/innovation*:** The universities will be at the forefront of agricultural research, conducting groundbreaking studies to address pressing challenges such as climate change, resource scarcity, and food insecurity. They will leverage advanced technologies and collaborate with national and international partners to generate innovative solutions with real-world impact.

Resource generation and industry affiliations: Strong partnerships with industry stakeholders, government agencies, and non-profit organizations will facilitate technology transfer, knowledge exchange, and commercialization of research outcomes in AUs. These collaborations will ensure that research innovations are effectively translated into practical applications that benefit farmers, agribusinesses, and consumers.

***Global interactions*:** Indian AUs will actively engage with the global community through collaborative research projects, student and faculty exchange programs, and participation in international conferences and consortia. These engagements will promote cross-cultural understanding, facilitate knowledge sharing, and enhance the global competitiveness of Indian agriculture.

***Socio-economic impact*:** In the near future, AUs will play a pivotal role in promoting inclusive growth, poverty alleviation, and rural development. They will empower smallholders through adaptable initiatives, technology adoption, and market linkages, thereby improving livelihoods and enhancing food security at the grassroots level.

***Ethical and sustainable practices*:** Indian AUs uphold the highest standards of ethics, integrity, and sustainability in their research, teaching, and outreach activities, and they will maintain their rigour in doing so. They will promote environment-friendly farming practices, biodiversity conservation, and social responsibility to ensure the long-term viability of agriculture and rural communities.

***Multidisciplinary practices*:** A multidisciplinary approach will be adopted across all AUs, fostering cognitive learning through the integration of diverse courses and skill sets. These educational approaches would cultivate leaders within universities who excel not only in singular domains but across various fields of science and agriculture.

9.1. Journey toward universities achieving world-class status

It is imperative to delve deeper to explore how an individual AU can strive towards achieving world-class status, regardless of its field or discipline. As per the latest world university rankings of QS in the area of Agriculture and Forestry, only 6 Indian AUs (GBPUA&T and TNAU amongst NAREES) have been ranked among the 420 Global AUs. This is below par for a country like India, which accounts for around 18% of the world population. This calls for a rigorous revamp in the AU higher education system that will help make a global footprint. Some key areas AUs would need to excel in are listed below.

9.1.1. Empowering educators for student-centric learning

There is a notable absence of formalized training pathways for prospective professors to adequately address student engagement and pedagogical challenges. It is imperative for educators to possess a deep understanding of students' individual learning styles and motivations to facilitate effective teaching. To bridge this gap, the establishment of a focused training or certification program is essential. Such a program would equip educators with the necessary skills and insights to tailor their instructional approaches and effectively engage with students in the classroom environment, thereby enhancing the overall quality of education delivery.

9.1.2. Quality of education

NEP 2020 aims to increase the higher education GER from ~27% to 50% by 2035. This goal will have a profound impact on agricultural education institutions. With 77 AUs and over 1,000 colleges offering courses in agriculture and allied sectors, catering to 200,000 students, there is ample capacity to focus on quality. The driving force behind making an enduring and impactful contribution will be a comprehensive, multi-disciplinary teaching model offering industry-relevant courses complemented with an intensely collaborative research ecosystem. These elements would support revolutionary changes in the realm of agriculture and higher education throughout India and lead to substantial research results that impact society as a whole.

9.1.3. Thriving research environment

The AUs will be central to furthering the research and innovation agenda for the sector. Promoting pure research and innovation that allows faculty and students of AUs to solve problems that positively impact society as a whole would be a key barometer of the AUs ' success during the *Amrit Kaal*. These universities will be at the forefront of agricultural research, conducting ground-breaking studies aligned to the priorities of the nation, which include climate change, food insecurity, sustainability, mechanization, among many more.

In 2047, a world-class AU will stand as a beacon of innovation, embracing advanced technologies and pioneering new approaches to addressing the challenges facing agriculture. Box 6 gives some futuristic vision and technologies characterizing such an institution.

Box 6. Vision and Technologies in world-class AUs of India

1. Interdisciplinary Research Centers

This would focus on the critical agricultural challenges. An example of this could be the Center for Climate-Resilient Agriculture that would bring together experts in agronomy, climatology, and data science to develop climate-smart farming techniques. Similarly, a Innovation Center for Food Security and Nutrition would explore innovative approaches to ensure food access and nutrition for all

2. AgriData Analytics Lab

AI-powered predictive models would analyze vast amounts of agricultural data, including weather patterns, soil conditions, and crop health, to optimize farming practices. For instance, AI-driven crop monitoring systems could detect early signs of pest infestations or nutrient deficiencies, enabling timely interventions to prevent yield losses.

3. Robotics and Automation Training & Development Lab

Labs such as these would work on the development of cutting edge technologies in all AUs as well as act as technical training centers for students, farmers and other stakeholders. eg: Autonomous drones equipped with sensors and cameras would survey farmland, monitor crop health, and report the data to AUs regularly.

4. Cutting Edge Curricula

New age courses such as Vertical Farming and Controlled Environment Agriculture (CEA) in the curriculum would help study how to produce high-value crops in urban environments under constrained environmental conditions and in a minimal space. Similarly, courses on 'Blockchain for Supply Chain Transparency' would revolutionize supply chain management in agriculture, providing transparency and traceability from farm to fork. This would open avenues for students to explore new realms within the agricultural ecosystem.

5. Existence of a Academic Consortium

A Quad-University-Industry collaboration with member organizations as a top engineering institution, a top medical institution, the agricultural

Contd...

university and the relevant industry would leverage their expertises to tackle the challenges that the world is facing today. Engineering innovations such as the 3D Printing if used for agri solutions would revolutionize the production of customized agri-tech solutions. Wit integration of this kind of a technique, students would be able to design and fabricate precision agriculture tools, irrigation systems, and greenhouse components tailored to the specific needs of different geographical locations. This democratization of innovating and manufacturing could eventually empower smallholder farmers and reduce reliance on centralized supply chains.

6. Farmer Training and Extension Programs

AUs would train thousands of farmers annually on new technologies and best practices through workshops and extension programs, further they would measure the impact on farmer adoption rates of these technologies and improvements in farm productivity.

9.2. Career readiness

A world-class AU would be known to produce students who are far more competent than their peers in other universities. While the quality of education is instrumental to the employability of the students, a world-class AU would exude a few more areas to rise above its peers, as given below.

(a) **Strong alumni networks:** AUs would have strong alumni networks that provide mentoring, networking, and job opportunities for current students and recent graduates. Programs where alumni visit the college and mentor students would be run in AUs to keep the students abreast with the latest industry developments.

(b) **Entrepreneurship and development cell (EDC):** By 2047, the Entrepreneurship and Development Cell (EDC) in a world-class AU would be a dynamic and forward-thinking hub dedicated to fostering innovation, entrepreneurship, and sustainable development in the agricultural sector. This cell would provide a multitude of services to students, some of which would be:

- ***State-of-the-art facilities***: The EDC would be equipped with cutting-edge facilities, including coworking spaces, maker labs, incubation centers, and presentation rooms. These spaces would be designed to inspire creativity, collaboration, and hands-on experimentation among students, faculty, researchers, and industry partners.

- ***Interdisciplinary collaboration***: The EDC would promote interdisciplinary collaboration by bringing together experts from diverse fields such as engineering, business, environmental science, and social sciences. This collaborative approach would facilitate the development of holistic solutions to complex agricultural challenges and encourage cross-pollination of ideas.
- ***Entrepreneurship programs***: The EDC would offer comprehensive entrepreneurship programs tailored to the needs of agricultural students and aspiring agripreneurs. These programs would include workshops, seminars, boot camps, and mentorship initiatives covering topics such as business planning, market research, funding strategies, and startup management.
- ***Startup incubation***: The EDC would operate a startup incubation program to support the development and growth of agricultural startups. Entrepreneurs with innovative ideas for new products, services, or technologies would receive mentorship, funding, networking opportunities, and access to specialized resources to turn their visions into viable businesses.
- ***Technology transfer and commercialization***: The EDC would facilitate the transfer of technology and intellectual property from the university to the marketplace. Researchers and inventors would receive assistance in patenting their innovations, licensing their technologies, and forming partnerships with industry collaborators to commercialize their discoveries.
- ***Social entrepreneurship initiatives***: In addition to commercial ventures, the EDC would support social entrepreneurship initiatives aimed at addressing pressing social and environmental issues in agriculture. Students and entrepreneurs would be encouraged to develop innovative solutions for sustainable farming practices, food security, rural development, and poverty alleviation.
- ***Networking and events***: The EDC would organize networking events, pitch competitions, hackathons, conferences, and industry showcases to connect aspiring entrepreneurs with mentors, investors, potential collaborators, and customers. These events would create a vibrant ecosystem of innovation and entrepreneurship within the university community.
- ***Global engagement:*** The EDC would foster global engagement by facilitating international collaborations, study abroad programs, exchange opportunities, and partnerships with

overseas universities, research institutions, and agribusinesses. This global perspective would expose students to diverse agricultural practices, markets, and challenges, preparing them for leadership roles in the global agri-food sector.

- ***Impact measurement and evaluation***: The EDC would measure and evaluate its impact on entrepreneurship, innovation, and sustainable development through key performance indicators (KPIs) such as the number of startups launched, jobs created, patents filed, revenue generated, and social or environmental outcomes achieved. This data-driven approach would enable continuous improvement and accountability.

9.3. Sustainability

A hallmark of a top-tier AU lies in its commitment to sustainability practices. Looking ahead, the vision for AUs involves embedding sustainability and climate change considerations into the core of their education curriculum. This strategic approach aims to nurture a workforce capable of providing global consultancy services in these vital areas. To achieve this vision, it's crucial to start preparing students from the outset of their academic journey. AU campuses play a pivotal role as living laboratories for sustainable practices. They should strive to achieve net-zero emissions and set an example as global leaders in addressing climate change challenges. By integrating sustainability into every aspect of campus life, from infrastructure development to waste management, AUs can demonstrate their commitment to a sustainable future and inspire the next generation of agricultural leaders (Box 7).

9.4. Funding

It is widely acknowledged that investing in research and education are amongst the most effective strategies for addressing agricultural issues (Singh *et al.*, 2022). While most agricultural research in India is conducted within the public sector, the overall agricultural research and development (R&D) remains inadequately funded. A recent study by Kandpal *et al.* (2024) has shown that for each rupee invested in research yields Rs 13.85 in return, and Rs 7.40 for extension services. In spite of this, in the fiscal year 2020-21, only about 0.54% of agricultural gross domestic product (GDP) of India was allocated to research, and 0.11% to extension services, significantly lower than global averages (Kandpal *et al.* 2024). The authors recommend that by 2030, investment in R&D should be increased to at least one% of agricultural GDP, and advocate for allocating more resources towards

Box 7. Sustainability Aspects for World-class AUs of India

1. Living Lab for Sustainable Agriculture

The university campus would be a carbon neutral campus fulfilling 100% of its energy requirements through the use of renewable energy sources. Also, the data on energy consumption, water usage, and waste generation would be tracked and publicly reported to showcase the effectiveness of sustainable practices.

2. Environmental, Social, and Governance (ESG) Cell

The cell would consist of experts from environmental background and would conduct regular surveys to measure student and faculty satisfaction with campus sustainability initiatives and natural resources.

4. Consultancy Services

Upon graduation, future students will possess the expertise to offer professional consultancy to industries on ESG, positioning themselves as global leaders in this domain.

5. Climate Resilient Technology and its Dissemination

In the future, agricultural universities, leveraging their expertise in climate change and sustainability, will develop climate-resilient technologies. These technologies will then be distributed to beneficiaries through extension services provided by agricultural universities.

research in livestock, fisheries, natural resource management, climate adaptation and mitigation, and addressing regional disparities in R&D.

Notwithstanding the above study, the revenue streams will exhibit significant diversification by 2047, enabling AUs to generate ample internal revenue, probably becoming largely or fully self-sufficient for budgetary issues. This will facilitate the advancement of multiple development agendas within the university, while government funding, if any, remains predominantly allocated to education and research endeavors. With the changing face of the world, a few of the sources of revenue for the universities could be:

- **Continuing education programs**: AUs would offer professional development courses, workshops, and certificate programs for professionals looking to enhance their skills or advance their careers. These programs could be tailored to meet industry needs and can attract participants from diverse backgrounds.
- **Research contracts & consulting services**: The AU would be a major contributor to the development of the region within its vicinity.

The government, non-profit organizations, small businesses, etc., would approach these institutions for providing consulting services in this regard. The institutions would utilize their faculty expertise to offer services such as research, data analysis, program evaluation, and strategic planning, leveraging the institution's intellectual capital to address real-world challenges. This would also be a lucrative option for the clients because it would save them huge on the costs they would incur if they offered this job to any other Private consulting firms.

- **Technology transfer and intellectual property:** An AU would commercialize the majority of its high-quality research outcomes, patents, and intellectual property developed by faculty and students and establish partnerships with industry bodies to license technologies, develop spin-off companies, or provide consultancy services based on innovative research findings.
- **Endowment management**: The AUs would use the returns generated from the endowment to support scholarships, research grants, infrastructure development, and other institutional priorities.
- **Customized training and workshops:** The AU would be a center for skill development for corporate clients, government agencies, and industry partners. A tailored program to meet specific training needs and objectives, leveraging faculty expertise and institutional resources.

10. Epilogue

The vast network of the Indian Council of Agricultural Research (ICAR) and Agricultural Universities (AUs) in India aims to cultivate a skilled and adaptable workforce to meet the challenges of a rapidly changing world. The educated individuals produced by the agriculture education system will lead innovations that ensure food security, environmental protection, and a sustainable future. Despite the presence of 77 AUs in the public sector, challenges persist, necessitating ongoing reforms and partnerships with global institutions and the private sector. Encouraging cross-state education through scholarships and fellowships further ensures a diverse pool of agricultural professionals ready to address tomorrow's challenges.

The journey toward achieving world-class status for Indian AUs requires continuous evolution and innovation. In envisioning the future of agricultural education, it is recognized that excellence extends beyond academic achievements. It involves personalized learning, immersive virtual experiences, data-informed teaching, and accessible knowledge dissemination. This holistic approach integrates cutting-edge teaching methodologies, groundbreaking research, entrepreneurial spirit, and sustainable practices. Indian AUs need to lead in innovation, leveraging advanced technologies and interdisciplinary collaborations to pioneer transformative solutions. From climate change mitigation to resource management, research should prioritize sustainability and real-world impact. Through alumni networks, entrepreneurship cells, and global engagement, a culture of innovation can be fostered that drives economic growth and societal development, ensuring a skilled workforce for food security, economic growth, and environmental sustainability. Sustainability is integral to India's civilizational ethos. It needs to be reflected in net-zero emissions, world-class infrastructure, and ethical practices. By integrating sustainability into all aspects of operations, precedence is set for responsible stewardship of natural resources and the environment.

Agriculture students should emerge as both experts and innovators, equipped to tackle complex sectoral challenges. Focus on employability and entrepreneurship ensures graduates become job creators. Achieving this vision demands a collective vision, dedication, and relentless pursuit of excellence. Through collaboration, stakeholder engagement, and forward-thinking policies, we can shape a vibrant and sustainable future for agricultural education, remaining relevant in the 21st century and beyond. Let us work together to redefine agricultural education by 2047 and beyond, shaping a brighter future for agriculture and society.

11. References

Agrawal, R. C. (2022). New paradigms in agricultural education in India. Indian Journal of Plant Genetic Resources, 35(3), 50–52. https://doi.org/10.5958/0976-1926.2022.00041.9

Agrawal, R. C., & Jaggi, S. (2024). Transforming agricultural education for a sustainable future. In K. C. Bansal, W. S. Lakra, & H. Pathak (Eds.), Transformation of agri-food systems (pp. 357–369). Springer Nature.

Agrawal, R. C., Pandey, P. S., Jaggi, S., Jain, V., Agnihotri, M. K., Sankhyan, S. K., & Verma, N. (2022). Achievements in agricultural education in independent India. In H. Pathak, J. P. Mishra, & T. Mohapatra (Eds.), Indian agriculture after independence (pp. 311–332). Indian Council of Agricultural Research.

All India Survey on Higher Education (AISHE). (2022). All India Survey on Higher Education (AISHE) Report, 2021-22. Ministry of Education, Government of India. https://aishe.gov.in/aishe/viewDocument.action?documentId=353

Indian Council of Agricultural Research (ICAR). (2021). Implementation strategy for National Education Policy-2020 in agricultural education system. Directorate of Knowledge Management in Agriculture, ICAR. https://www.icar.org.in/sites/default/files/2022-04/New%20Education%20Policy-2020.pdf

Indian Council of Agricultural Research (ICAR). (2023). Model Act for higher agricultural educational institutions in India - 2023. Indian Council of Agricultural Research.

Indian Council of Agricultural Research (ICAR). (2024). ICAR education portal. https://education.icar.gov.in/HomePage

Indian Council of Agricultural Research - National Agricultural Higher Education Project (ICAR-NAHEP). (2023). Annual report (2022-23). https://nahep.icar.gov.in/pdf/NAHEP-Annual%20Report-2022-23.pdf

Kandpal, A., Birthal, P. S., & Mishra, S. (2024). From research to impact: Payoffs to investment in agricultural research and extension in India. Policy Paper 44, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP).

Ministry of Education (MoE). (2023). PM launches 'Viksit Bharat @2047: Voice of Youth'. Government of India. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1985077

Ministry of Education (MoE). (2024). National Education Policy, 2020. Government of India. https://www.education.gov.in/nep/about-nep

Ministry of Finance (MoF). (2024). Economic survey 2022-23. Department of Economic Affairs, Government of India. https://www.indiabudget.gov.in/economicsurvey/

National Academy of Agricultural Sciences (NAAS). (2021). New agricultural education policy for reshaping India (Policy Paper No. 99). National Academy of Agricultural Sciences.

Paroda, R. S. (2018). Reorienting Indian agriculture: Challenges and opportunities. CAB International.

Pathak, H. (2024). Transforming agricultural education for aspiring India. Lal Bahadur Shastri Memorial Lecture, 62nd Convocation, The Graduate School, ICAR-Indian Agricultural Research Institute.

Randhawa, M. S. (1979). A history of agriculture in India. Indian Council of Agricultural Research.

Singh, R. B., Paroda, R. S., & Dadlani, M. (2022). Science, technology and innovation. In R. Chand, P. Joshi, & S. Khadka (Eds.), Indian agriculture towards 2030: Pathways for enhancing farmers' income, nutritional security and sustainable food and farm systems (pp. 213–250). Food & Agriculture Organization of the United Nations; Springer. https://doi.org/10.1007/978-981-19-0763-0

Sinha, S. K. (2000). Education for agriculture in India: Time for a change. Current Science, 79(3), 302–310.

Soam, S. K., Subbanna, Y. B., Rathore, S., Sumanth Kumar, V. V., Kumar, S., Vinayagam, S. S., Rakesh, S., Balasani, R., Raju, D. T., Kumar, A., Rao, N. S., Krishnan, P., Marwah, S., Agrawal, A., Srinivasarao, Ch., & Agrawal, R. C. (2023). Academia-industry linkages for sustainable innovation in agriculture higher education in India. Sustainability, 15(23), 16450. https://doi.org/10.3390/su152316450

Tamboli, P. M., & Nene, Y. L. (2013). Modernizing higher agricultural education system in India to meet the challenges of 21st century. Asian Agri-History, 17(3), 251–264.

Thammi-Raju, D., Soam, S. K., Srinivasa Rao, N., Kumar, A., Sumanth Kumar, V. V., Kumar, S., Rathore, S., Senthil, S., Vinayagam, B. M., Yashavanth, B. S., Krishnan, P., Marwaha, S., Venkateshwarlu, G., Srinivasarao, Ch., & Agrawal, R. C. (2021). Curriculum development framework for agricultural education. National Agricultural Higher Education Project – Component 2, Indian Council of Agricultural Research (ICAR), National Academy of Agricultural Research Management (NAARM). https://nahep.naarm.org.in/file_uploads/development_framework_cur.pdf

Tripathi, H., Agrawal, R. C., & Pathak, H. (2023). Human resource requirements in agriculture in India. Indian Council of Agricultural Research. https://nahep.icar.gov.in/pdf/Human%20Resource%20Requirement%20in%20Agriculture-Document.pdf

University Grants Commission (UGC). (2023). Consolidated list of all universities in India as on 31.12.2023. UGC. https://www.ugc.gov.in/oldpdf/Consolidated%20list%20of%20All%20Universities.pdf

13 Agricultural Extension

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1. Context

Indian agriculture has witnessed extraordinary progress since the country's independence in 1947. There has been a giant leap in the production of food grains from just 50.82 Mt in 1950-51 to an all-time high of 330.5 Mt in 2022-23. However, the rapid increase in the country's population, predicted to reach a whopping 1.61 billion in 2047, may create serious challenges for the entire agricultural production system, especially in the face of ever-increasing climatic adversities. In agriculture-based economies, extension and advisory services play an important role in sustaining growth by means of timely and efficient information dissemination and capacity building, aiding faster diffusion of technologies (Kokate *et al.*, 2016). The extension service delivery system is a complex mechanism of integration, coordination, and communication dealing with farm technologies on the one hand and the socioeconomic dimensions of the target audience on the other. In a given micro-situation in the absence of reformed extension services, the program delivery to the targeted clientele remains inadequate. Hence, strong extension innovations/ O&M reforms are needed both in public and private systems. Despite the various reforms in extension, there remain critical gaps and limitations, which have a large bearing on livelihoods and well-being of small and marginal farmers, food and nutritional security, agro-ecosystems and their sustainability (Bhattacharyya *et al.*, 2018; Roy Burman *et al.*, 2021). In the future, the extension service delivery should be more visible, efficient, and location-specific and should be duly supported by public policies, investments, incentive-linked good agricultural practices (GAPs), market

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reforms, scaling innovations, and input augmentation (Mahapatra *et al.,* 2022; Sangeetha *et al.,* 2018).

Sound extension strategies contributing to the self-sufficiency of food grains at the global level will help project the country as a *'Viswaguru'* in agriculture. India used to be a deficit country in most of the food commodities at the time of independence but has now emerged as one of the leaders in agricultural exports. Such a transformation has become a global success story to emulate by many developing countries. The country's agricultural extension system has contributed enormously to realizing the success. However, the contribution of the public agricultural extension system is unquantified to date. Recent studies have reported that access to KVK (Krish Vigyan Kendra), the main pillar of the public agricultural extension system in India, increases the net farm income by 11%, an average of Rs 3,674 per hectare and per capita annual household income by Rs 419 on average (Kumar *et al.,* 2019). Such encouraging results dictate that there is an urgent need to enhance the outreach of the effective extension models by strengthening linkages between research and extension and integrating private sector efforts. The capacity-building programs organized for the field extension functionaries and farmers on a regular basis in varied topics by several organizations need to be streamlined through setting priorities and convergence of extension efforts, and increased use of social media. The extension research areas are decided based on the inputs received from farmers, various academic and semi-academic stakeholders, and are used to evolve an efficient extension system. Future extension research needs to focus on systems interplay, convergence, agribusinesses and entrepreneurs, App-based ICTs, extension for the unreached, climate change adaptation, etc. The present chapter discusses the extension strategies to be implemented and the roadmap to be followed in the *Amrit Kaal* for greater outreach and more effectiveness in extension service delivery.

2. Evolution of Extension and Advisory Services in India

The root of extension services can be traced back to 1800 B.C. However, the modern extension services started with the infamous 'potato famine' in 1845 in Ireland (Swanson et al., 1997). In developing countries, although commodity-related technical advice used to be provided during the colonial times to farmers, the National agricultural advisory services were not formally established until the 1950s and 60s. Extension was included in the university mandate with the inception of 'university extension' in the USA during the 1860s. The scope of extension expanded during the nineteen fifties when the subcontinents of Asia and Africa started laying primary importance on agriculture for increasing food production and educating the farming community with improved farming practices (Antholt, 1994).

Extension and advisory services in India gradually evolved over a period of time. It involved the evolution of the program delivery models, intensive use of ICTs, upgradation of field functionaries, market integration, and enabling policy environment. Two pre-independence programs, the Community Development Program (CDP) (1952) and the National Extension Service (NES) (1953), marked the formal beginning of extension and advisory services in the country. The pre-Green Revolution programs like, Intensive Agricultural District Program (IADP)(1961) and Intensive Agricultural Area Program (IAAP)(1964), followed by National Demonstrations (ND) (1965), Farmers Training Center (FTC)(1966), Small and Marginal Farmers Development Agency (SMFDA)(1971), *Krishi Vigyan Kendras* (KVK) (1974) and Lab to Land program (LLP) (1979) further formalized the structure of extension and advisory services. In 1974-75, a major extension intervention through the World Bank Funded program raining and Visit (T&V) system helped in restructuring the extension system. Following its significant impact, it was expanded throughout the country from 1984 to 1995 through the National Agricultural Extension Project (NAEP). Further, the process of Extension Reforms was strengthened under National Agricultural Technology Project (NATP, 1998) by establishing at the district level Agricultural Technology Management Agency (ATMA), which at present covers 676 districts in 29 States/3 3 UTs under the National Mission on Agricultural Extension & Technology (NMAET). The present-day extension emphasizes holistic empowerment of farm households from different perspectives- production, marketing, price negotiation, skill development, entrepreneurship, health and nutrition, and gender neutrality. Cooperatives, Farmers Clubs, Self-Help Groups (SHGs), Farmers Interest Groups (FIGs), Commodity Interest Groups (CIGs), Farmer Producer Organizations (FPOs), and Farmer Producer Companies (FPCs) have emerged as important mechanisms for leveraging extension and advisory services.

3. From Production to Nutrition: Paradigm Shift in Extension Approaches

The approaches followed in extension service delivery are not static. They vary according to the clientele groups, commodities, purposes, contexts and locations. Axinn (1988) observed different extension approaches followed throughout the world. The prescriptive extension approach, which is a typical top–down approach, has been extensively followed in the country for a long time. However, a gradual shift is being observed these days. The following are some of the good examples of the visible shift:

3.1. Nutrition-sensitive extension

Nutrition-sensitive agriculture (NSA) is a food-based approach putting nutritionally rich foods, dietary diversity, and food fortification at the center of agricultural development (FAO, 2014). The agriculture-nutrition pathway envisages that agriculture does not provide nutrition alone; it is a source of income for expending on food and non-food items (Kadiyala et al., 2014). A holistic food system approach is required to address the challenges of unsafe foods and poor diets. The issues of food safety, nutrition, and food security are inextricably linked and connected with the overall food ecosystem comprising food supplies, transportation, retail marketing, consumption, and demand (Srivastava *et al.,* 2023; Paul *et al.,* 2018). A convergence-based multi-agency extension approach is required to address the problems of hunger and malnutrition by enhancing the capacities of the public and private sectors through extensive use of information technology and different forms of media including social media in dissemination of relevant information and technologies to farmers, especially women farmers (Satyapriya *et al.,* 2018). Extension professionals need to acquaint themselves with the local organizations and knowledge systems regarding crop choices, nutrition-sensitive agricultural practices, dietary diversity, homestead nutri-gardens, small-scale livestock farming, promotion of nutri-rich varieties, and social safety nets. The role of extension does not limit itself to the dissemination of technologies and information. It also envisages sensitizing farm families through social and behavioral change communication with the nutritional benefits of diverse dietary practices and healthy lifestyles (Sangeetha et al., 2019). The Indian Council of Agricultural Research has been addressing the issues of women's nutrition through a systematically planned program called 'Nutrition Sensitive Agricultural Resources and Innovation (NARI)'. The program follows a food system approach that puts the nutrition-rich food crops, dietary diversity and food fortification at the center of agricultural development. NARI aims to promote family farms for whole family nutrition, skill development of women and youth, including school students in this direction, creating awareness about fortification of local foods and dietary diversity, designing nutrition-rich, low-cost, balanced diet (*thalis*) and establishing nutri-smart villages. Several government schemes are also aligned with nutrition-sensitive agriculture, e.g., the 'Half Acre Model' of Telangana aims to help women farmers to meet their nutritional requirements from vegetables. Given that gender participation in farming is skewed toward women, ICAR has been addressing issues of nutrition through the NARI, as discussed previously. Some state governments have been addressing these issues by implementing such schemes. The Participatory Learning and Action – Linking Agriculture to Nutrition and Natural Resources (PLA-LANN) in Odisha and 'Reliance Nutrition Gardens' (RNGs) in Maharashtra are notable schemes that aim at improving dietary diversity and nutritional outcomes through innovative strategies including community meetings, group counselling, individual home visits to target groups, and supply of garden inputs (seeds). This model follows a staggered production design and handling to ensure year-round availability of vegetables for home consumption and the market.

3.2. Gender-neutral extension for better nutritional outcomes

The term 'gender' is often viewed in a narrow sense. It is rather a connotation of social attribution instead of biological features and is often used interchangeably for men and women. Food and nutrition security has four pillars: availability, accessibility, utilization, and stability. From a nutritional perspective, the utilization of food is the most important. While most government schemes focus on food availability and accessibility, ignoring utilization. The traditional processing protocols need to be based on women-centric nutritional education involving ANM, *Aanganwadi*, ASHA and other frontline workers. ICT can prove a handy tool in spreading nutritional information on a larger scale with little time and cost. However, it is important to acknowledge the digital divide. Impoverished women have little access to gadgets and lack digital literacy. Mass media, including radio and television, can still play an important role. Compared to men, women have less access to resources, finances, information, technologies and food safety nets, while they are more efficient in improving agricultural productivity. It is, therefore, essential to revisit agricultural development, social safety and extension programs and restructure these to reduce gender disparity. The missing link between agriculture and nutrition envisages identifying critical gender gaps in nutrition and accordingly designing and developing gender-appropriate and gender-responsive programs (Paul *et al.*, 2022). A two-fold strategy comprising a food-based approach for promoting the cultivation of nutrient-rich crops and evolving value chains from farm to fork, and a non-food-based approach addressing gender issues and social dimensions is required. The women members of SHGs may be persuaded to cultivate seasonal vegetables in their homesteads or gardens. Government programs targeting women through collectives can be an effective mechanism to address women's empowerment issues. There are many other success stories. Supporting smallholder farmers with Rs 1-2 lakh/family for developing nutrition gardens at the village level in Himachal Pradesh offers considerable scope for replication in other states. Likewise, establishing Nutri-smart villages in Madhya Pradesh and Chhattisgarh through the partnership of state governments and KVKs is another way of scaling up nutri-sensitive agriculture. The innovative concept of '*ApniKyari, ApniThali'* in Bihar through small kitchen gardens merits attention for its replication and scaling up.

3.3. Major extension models in the country (See Box 1)

Box 1. The major extension models prevailing in the country

S. No.	Model	Guidance, monitoring, and control	Scale of operation
1.	Research Institution Outlets (RIOs)	Operate under State Agriculture/ Horticulture/ Veterinary Universities and ICAR institutes	Provide strong technology outreach windows like adopted villages, blocks & innovative systems of KVKs, with focus on technology validation, demonstration and dissemination.
2.	Development Department Outlets (DDOs)	Operate under the State Departments of Agriculture, Horticulture, Animal Husbandry, Dairy, Fisheries, Sericulture, etc.	Carry out extension through various State/ GoI schemes. Agricultural Technology Management Agency (ATMA) -a semi-autonomous institution at district level has successfully attempted restructuring field extension services.
3.	Commodity Boards (Tea, Coffee, Spices, Coconut, Fisheries)	Department of Commerce, Govt. of India	Provides extension, production and market/ export promotion support.

Contd...

S. No.	Model	Guidance, monitoring, and control	Scale of operation
4.	Private sector extension service providers including agri-startups and entrepreneurs	Self	Entrepreneurs /input agencies supplement extension efforts while promoting their own products and services.
5.	Farmer Groups/ Organizations/ Cooperatives	Self	Mobilize farmers' participation.
6.	Non-Government Organizations (NGOs)	Self	Operate at local, national, regional, and international level. Connect through participatory and mobilization approaches.
7.	Mass Media (traditional, print and electronic)	Self	Play important role in information dissemination.
8.	Social-media platforms	Self	Gaining major space in the information dissemination processes.

3.4. Major constraints in extension service delivery

The extension models are not free from constraints which considerably affect the technology dissemination process. The most important constraints faced in extension service delivery are as follows:

3.4.1. Poor extension worker-farmer ratio

Latest estimates suggest that the extension worker: farmer ratio in the country is less than 1:5000, which is much lower than in developed countries (Roy Burman *et al*., 2021). The extension functionary: operational farm holding ratio is very high (1:1162), as against the recommended 1:750 for the national level and 1:400 for hilly areas.

3.4.2. Inadequate investments and extension infrastructure

Critical investment gaps exist in investment and infrastructure. The share of expenditure in agricultural extension and training as a percentage of total agricultural GDP has witnessed stagnancy (Joshi *et al*., 2015). Extension expenditure as a% of GDPA has remained almost unchanged, ranging between 0.12 and 0.16% in the last two decades.

3.4.3. Gaps in need-based deployment of extension functionaries at various levels

Major scarcity of extension functionaries prevails at different levels. A majority of the states have their extension staff only up to the block level. The deployment of extension functionaries up to the village level is really difficult, with only 0.12 million extension professionals in India as against 7.13 million local agriculture extension personnel in China. About 40% of the extension functionaries in the agriculture department are not in a position (Gulati *et al.* 2018). The vacancy position is particularly alarming in tribal and distant areas, which are mostly in need of extension services.

3.4.4. Limitations with policy support and systemic inadequacies

Though the KVKs, ATMA, and other grassroots extension organizations, including the state departments of agriculture, undertake extension programs and capacity-building initiatives for empowering farmers, there is a specific need to bring in an extension policy for promoting environment-friendly, climate-resilient, and sustainable agriculture.

3.4.5. Inadequate capacities of the district /block-level extension agencies

District and block-level extension agencies are hardly equipped with adequate manpower, infrastructure, and capacity-building resources to extend their outreach and cater to the needs of every farmer within their area of jurisdiction. However, recent studies have shown that investments made in expanding India's network of KVKs have been quite remunerative, as the benefit-cost ratio of expenditure on KVKs ranges from 8 to 12 (Kumar et al., 2019).

3.4.6. Lack of convergence of extension efforts

The grassroots extension agencies generally lack convergence with public and private entities. This often results in duplication of efforts and inefficient resource use.

3.4.7. Lack of private extension initiatives

Extension initiatives in India are generally public-funded, though some private initiatives can also be found scattered. Some notable private extension initiatives are *e-Choupal* (ITC), Tata Kisan Sansar (Tata Group), and Village Knowledge Center (MSSRF). It is desirable that private and philanthropic initiatives fill the void left by the limited outreach capacity of the public extension system.

3.4.8. Inadequate R&E linkages and feedback management mechanisms

There exist inadequacies in establishing a strong linkage between research and extension. Ideally, farmers' feedback should provide the foundation for designing research programs in agriculture. The research problems should prioritize addressing farmers' felt needs. But often there remains a gap in taking up research programs based on farmers' field problems. A robust linkage between research and extension, with due consideration of the feedback mechanism, will increase the efficiency of the entire R&E system.

3.5. Extension innovations, reforms and reorientation

The agri-food system transformation during the *Amrit Kaal* will be possible when the extension system embraces a series of paradigm shifts from incremental to disruptive approaches. Existing Krishi Vigyan Kendras (KVKs) in more modern forms will enable rapid dissemination of these innovations. The reforms should start with agricultural education. Drastic changes in curriculum with extensive hands-on training to Agricultural extension students on digital tools, AI and big data, and separate courses on them are needed for the hour. The outreach, interplay and performance of extension models need to be improved by widening the sectoral and area coverage, promoting partnerships and resource sharing, enhancing integrated delivery, improving penetration to the small producers, and promoting chains of extension agents across the production systems and also to build human resource capacities for efficient program delivery.

3.5.1. Knowledge agent

There is a need to create a new cadre of advisors at the district level whose task may be to guide farmers in accessing technology, new knowledge and information.

3.5.2. Digital transformation

Embracing the latest digital technologies and platforms to enhance the delivery of extension services, to provide access to information, training, expert advice and blend them with critical inputs, supply is crucial. Social media (WhatsApp, Facebook, Twitter, Instagram), Blogs, and App-based services need to be used effectively by networking farmers and offering them context-specific information, eco-region-wise. Farm-portals like "*Kisan SARATHI*" providing information on production/ protection technologies, *e*-advisories, inputs/prices, *e*-marketing, *e*-platforms and mobile applications need to be promoted.

3.5.3. Data-driven decision making

Leveraging data analytics and remote sensing technologies to collect and analyze agricultural data, weather patterns, and market trends, and to provide personalized advice and recommendations to farmers will help them make informed decisions about crop selection, pest management, irrigation, and market opportunities. Artificial Intelligence (AI), big data analytics, machine learning, etc., should be promoted to provide appropriate and evidence-based advisory services. ICT, AI, and big data analytics platforms should be used effectively, especially during the pandemic and such crises. Advanced technologies like drones, robotics, remote sensing applications, sensors, machine learning, block chain, internet of things (IoT), as well as artificial intelligence (AI) need to be extensively used for precision farming, improved farm management, and providing real-time data. To ensure this, extension agents and progressive farmers should be oriented and trained by the state agriculture universities, ICAR institutes, MANAGE, EEIs, SAMETIs, and organizations working in this line.

3.5.4. Knowledge networks and communities of practice

Facilitation in the formation of knowledge networks and communities of practice, both online and offline, will encourage farmers, researchers, and extension professionals to share experiences, best practices, and innovative solutions. This can foster peer learning, collaboration, and the dissemination of localised knowledge. The linkage between common service centers (CSCs), operating under the Ministry of Information Technology and KVKs should be built to reach the last mile. Further, *Kisan* Call Centers (KCCs) providing country-wide common eleven-digit toll-free number 1800-180-1551 could be used effectively. The rural tele-centers could also be used for better information management.

3.5.5. Participatory and farmer-centric approaches

Shift from top-down to participatory and farmer-centric model involving farmers in the co-creation of extension programs and initiatives, ensuring their needs, preferences, and feedback will strengthen farmer-to-farmer knowledge exchange and learning through farmer field schools, study circles, and demonstrations. It should also include promotion and transformation of Farmer Producer Organizations (FPOs), Farmer Producer Companies (FPCs) and Agricultural Cooperatives (ACs) into Smart Production and Aggregation Centers.

3.5.6. Strengthening agricultural extension services

Equipping extension advisors with updated knowledge and tools to promote climate-smart and sustainable agriculture practices will help farmers adopt resilient farming techniques, conserve natural resources, reduce greenhouse gas emissions, and mitigate the impacts of climate change. It is further necessary to provide guidance on organic farming, agroforestry, water management, and biodiversity conservation. It would require continuous investment in the capacity building of extension advisors to enhance their knowledge and skills. Offering regular training programs on emerging technologies, innovative practices, and communication strategies, and fostering partnerships with academic institutions, research organizations, and private sector entities will facilitate knowledge transfer and professional development.

3.5.7. Value chain development

Expansion of the scope of extension services beyond production to include post-harvest management, value addition, and market linkages is vital for the farmers to understand market demands, facilitate access to finance and technology, and support the establishment of farmer-producer organizations. Encouraging entrepreneurship, development of agribusiness enterprises, strengthening extension in upstream, mid-stream and downstream with functional collaborations harnessing emerging AgTech and start-up ecosystem is important.

3.5.8. Behavioral change communication

Behavior change communication techniques have to be applied to influence farmers' attitudes and behavior. Social media, interactive media, and community engagement techniques promote the adoption of innovative technologies and practices, improved nutrition, gender equality, and sustainable farming. Field days, farmers' fairs, campaigns, vernacular press, etc., should be promoted as supportive extension methods. The specific role of media in extending advisory services to farmers needs to be recognized and promoted as per agro-climatic and socioeconomic needs.

3.5.9. Women empowerment in agriculture

Recognizing and promoting the vital role of women in agriculture, developing gender-sensitive extension programs that address the specific needs and constraints faced by women farmers, offering training and support in areas such as financial literacy, access to credit, and decision-making in farm management has been put on priority since long.

3.5.10. Greater space to the private sector

There is a need to adopt a pluralistic approach involving multi-agencies such as civil society organizations, NGOs, small business entities, besides big corporations. Various ways of financing, such as paid extension, private extension, revenue model of extension, etc., need to be explored for the financial sustainability of the extension system. A mechanism may be implemented to engage Agribusiness MBAs, IT graduates and farm youths (including women) to provide advisory services on a 'payment basis (paid extension). This will ensure quality advisory services to the farmers without any dissemination loss. In fact, there is a need to promote private paid extension (PPE) services in commercial/ horticultural crops, secondary and specialty agriculture requiring specialized technical backstopping. Further, efficient input quality testing, soil and water testing, organic produce testing, value chain, etc, could be the options for involving youth in agriculture, requiring skill-oriented extension innovations. Learning from successful private sector models innovated by BAIF, ITC, Jain Irrigation, IFFCO, etc., could be a good beginning to accelerate this process.

3.5.11. Nutrition-sensitive extension

There is a need to promote nutrition-sensitive agriculture and an ecosystem approach to sustainable agriculture. Intelligent agri-food value chains and nutri systems need to be in place for the nutritional security of the nation, alongside empowering farmers to enhance their farm income. Establishment of nutri-smart villages at the cluster level has already been initiated by many agencies. Evidence-based health and nutrition programs may be integrated in the extension system.

3.5.12. Commodity-specific cluster approach

The commodity-specific cluster approach may be promoted to provide end-to-end services. Outreach programs such as front-line and field extension systems may be emphasized. Addressing depression, stress-strain and psychological issues faced by farmers and improving their mental health should also be on the agenda of outreach initiatives. There is an urgent need for organizing farmer/farm women knowledge groups (FKGs/FWKGs), eco-region-wise, around the commodities/ farming systems through FPOS. It will be advantageous if using the internet in rural

India, enabling direct link to the farmers and *e-Choupal*-like initiatives, is enhanced for supply chain efficiency.

3.5.13. Strengthening mass broadcast

The dedicated channel on agriculture - DD *Kisan*, radio broadcasts and community radio stations need to be strengthened for effective farmer-related knowledge dissemination. For this, there is a need to revisit these programs and have an external review to make them more efficient, relevant and effective. This needs to be done on priority by constituting a high-level committee by the Ministry of Agriculture and Farmers Welfare.

3.5.14. Farm-journalists network

A state-specific online platform for networking of agri-journalists needs to be created, their knowledge and skills related to agriculture need to be updated, and this platform should be utilized for quick dissemination of agricultural technologies through their magazines, newspapers, electronic and other media. National Network of Agri-Journalists (NNAJ), initiated by MANAGE, should be replicated at the State/ district level involving SAUs and KVKs-ATMA jointly.

3.5.15. Agri-film festivals

As practiced by MANAGE at the national level, agri-film festivals need to be organized in every state to encourage the capture of local innovations and success stories. The best films may be used in extension activities to motivate farmers.

3.5.16. Value-added agromet and agro-advisories

The agromet and agro-advisory services should be upscaled and out scaled to the farmers below the block level. The climate resilient village model of the ICAR needs to be replicated and up-scaled, suited to different agro-ecosystems. Greater focus should be given on energy-efficient agriculture to minimize GHG emissions and move towards a carbon-neutral economy.

3.5.17. Rural youth-center entrepreneurship and value chain development

Mechanisms need to be developed to reach to more and more rural youths, generating and sustaining their interests in pursuing agriculture-based livelihoods through entrepreneurship and value chain development programs. It will create gainful rural employment and retain them in agriculture. Similarly, business managerial skills of rural youth may be enhanced to enable them to venture into small agri and allied start-ups. Youth engagement strategies would require dignified and rewarding livelihoods; increased equity and rights to resources; enhancing knowledge, education and skills; and scaling sustainable innovations to help farmers reduce the cost of inputs and enhance their income by linking to markets for better livelihood. The Michigan State University's Global Youth Advancement Initiative (GYAI) model could also be experimented with to motivate youth.

3.5.18. Convergence and facilitation

Farmer-scientist interaction should be increased through the village adoption program. Also, a mechanism for the convergence of schemes and programs for effective extension delivery for the benefit of the farming community needs to be developed. The best extension worker and extension organization at the state and district levels need to be recognized and awarded. To bridge the shortage of manpower in the extension system, the facilitator model of MANAGE may be replicated by other extension organizations. The District Development Managers (NABARD), ATMAs and KVKs need to organize orientation camps jointly at the district/block level involving FPOs, NGOs, *Gram Panchayats* and retired extension professionals, for enhancing awareness of farmers (including women and youth) to take advantage of existing central and state-sponsored schemes. Farmer FIRST approach needs to be promoted with a focus on the critical needs of farmers and options for their redressal. The schemes like One-District-One-Product and Agricultural Infrastructure Fund need to be promoted using a niche area extension approach.

3.5.19. Capacity building of FPOs

Farmers and farmer producer organizations (FPOs) need to be involved in planning, implementing, and monitoring extension activities right from the beginning. MANAGE FPO Academy should strengthen emerging FPOs through capacity building of office bearers, hand-holding in business plan development, and facilitating forward and backwards linkages.

3.5.20. Leveraging CSR funds

Appropriate extension systems need to explore and leverage CSR funds for agriculture development and facilitate the transformation of the retired agri-professionals. There is a need to promote ex-servicemen as agri-preneurs through appropriate training programs and involving them in secondary agriculture. There is a dire need for aggressive and vibrant extension efforts on agroforestry for carbon sequestration right from seed to consumer with a value chain approach to ensure economic and ecological sustainability of farming.

3.6. Strengthening the research and extension linkages

The research and extension (R&E) linkages should be strengthened at the national, regional, state, district, and block levels. A framework on technological options specific to different agro-climatic conditions should be prepared through joint-coordination committees involving diverse stakeholders. These can be scaled out and monitored periodically. The impact of these technologies needs to be assessed for further spread. For effective technology transfer, direct involvement of scientists is essential to eliminate dissemination loss, especially in areas such as NRM, IPM, INM, conservation agriculture (CA), organic farming, farm mechanization, climate-smart agriculture, and crop diversification. Multi-disciplinary, inter-institutional efforts towards translational research can accelerate the adoption of new technologies backed by enabling policies and commensurate funding. Strong research-extension partnership and coordination mechanisms for scaling new technologies are the key to faster agricultural growth. The future extension-research coordination strategies may also involve and learn from international and private sector organizations. MANAGE, SAMETIs, ATARIs and the Directorates of Extension of the SAUs should have a strong extension research window. MANAGE needs to consider promoting "Field Extension Labs/ Centers of Excellence" in the critical areas in the selected SAUs/private extension systems. Extension research outcomes should be ploughed back for reforming existing operations and policies, for which suitable state-specific mechanisms also need to be developed.

3.7. Policy Interventions and reforms

To reach the ultimate goals of effective extension service delivery in the country, there is a need to revisit the reforms and make necessary policy interventions. Crucial extension reforms being promoted and practiced in India so far can be categorized as follows:

- Innovating institutional arrangements in the public sector for technology delivery.
- Strengthening public-private partnerships.
- Integrating the extension needs of allied sectors and disadvantaged areas/groups in the outreach programs of the frontline extension.
- Empowering farmers, FOs, FPCs, FIGs, and Farmer Cooperatives.

- Augmenting R&E linkages at various levels.
- Intensive use of media, ICTs and internet platforms.
- Promoting agri-start-ups, entrepreneurships, business incubation, value chain and market-led extension interventions.
- Involving farm youth and women through focused extension strategies with institutional support (ARYA, RAFTAR).
- Skilling farmers, field functionaries and other stakeholders, facilitating enhanced adoption of organic agriculture, climate resilience, and agri-business opportunities.

3.7.1. Curricula reforms

Curricula-based education at the basic and advanced levels for students is crucial for developing competent extensionists, including scientists, academicians, consultants, development functionaries, and service providers. Understanding the scientific logic of effective extension service delivery from at least four perspectives – organization, physical and financial resources, manpower, and end-users. Refinement of the extension curricula at the undergraduate as well as postgraduate levels is highly sought after to enhance scientific temperament and match the desired competency among students. The agricultural universities (AUs) need to revisit the course curricula for agricultural extension and bring in needed reforms to meet the current expectations and make them more relevant and purposeful. Diversified agriculture, secondary agriculture, specialty agriculture, value chain and agricultural marketing, including export options, demand innovations in agricultural extension education. This is an important and urgent matter that should be addressed while aligning with the National Education Policy (NEP) expectations.

3.7.2. Improving financial provisions

Improving the funding for extension services is essential to make them more effective and efficient. Financial provisions should be improved by allocating more funds for agricultural extension activities by the MoA&FW and ICAR. Leveraging higher allocation for extension activities under CSR funds by the corporate sector related to agriculture and allied fields requires policy talks at the higher level and rigorous persuasion. There is a need to revisit and strengthen the National Mission on Agricultural Extension and Technology. ICAR needs to initiate an urgent action for the National Agricultural Extension Project to be supported by a donor such as the World Bank to pilot innovative reforms in agricultural extension. Financial provisions for a Mission on Youth for motivating them to become extension/advisory agents and entrepreneurs and establishing the Agriculture Innovation Fund at the Council level to promote farmer-led innovations may prove to be a game changer. Objective-oriented and module-based public-private partnerships (PPPs) are likely to promote and improve the competency and capacities of young extension agents to provide advisory services on a payment basis for faster scaling of innovations and desired benefits for the end users. For the implementation of programs, a well-coordinated approach with delineated responsibilities to the Heads of KVKs would have a multiplier effect.

3.8. South-South collaboration

Since there are similarities in socio-economic and agroecological characteristics of agricultural households and farms of India and its neighboring countries, the innovative extension models followed in the neighboring countries may be adopted. Agriculture portal (*Krishi Batayon*), digital farmer database and agriculture profile, farmer-friendly call service, direct communication with the local extension workers, farmers' window-problem identification by matching image library, *Krishi* Bioscope- use of YouTube video channel, e-pesticide prescriber, digital crop clinic, and urban agriculture are practiced in Bangladesh. Establishment of Agri-product Marketing Bureau (AMB) to facilitate linkages between farmers and traders, initiation of agriculture and livestock business plans, online seed demand and supply management, sourcing local food and rooftop gardening and farming by women, as done in Nepal, can be considered. Expansion of industrial investments to promote the commercialization of farming, encouraging entrepreneurship and promoting sustainable agriculture, as done in Sri Lanka. Promising innovations and reforms in agricultural extension promoted in India, Bangladesh, Nepal and Sri Lanka need to be clearly understood for their suitability for adoption in the respective countries. There is an urgent need for the establishment of a regional 'South Asia Forum for Agricultural Extension (SAFAE)' for knowledge sharing relating to extension innovations, strategies, experiences relating to successful models, etc. Such a Forum could also exchange expertise, organize regional dialogues, and take up mutually agreed-upon collaborative pilot projects. For this, institutional support could be ensured through ICAR Extension Division, MANAGE, Trust for Advancement of Agricultural Sciences (TAAS), etc. in India and concerned nodal organizations in Bangladesh, Nepal and Sri Lanka. Adequate funding support from national lead organizations and international organizations/funding agencies such as the World Bank, IFAD, ADB, USAID, SAARC Secretariat, etc. could be sought.

4. Envisioning Extension For 2047

It is assumed that India in the year 2047 will become a developed nation, and the country will witness sea changes in the agricultural front. The population engaged in farming will drastically fall; therefore, the per capita availability of agricultural land may increase. Amidst urbanization taking place rapidly, less land will be available for agriculture by 2047. There will hardly be an option left other than breaking the yield ceiling to ensure food security. The state agriculture departments will promote hi-tech agriculture with much emphasis on precision farming for cost-cutting and operational efficiencies. Water-saving technologies, carbon credit, carbon farming, and net-zero emissions will be at the top of the agenda. There will be added thrust on secondary agriculture, processing, and value addition since packaged and pickled vegetables, fruits, value-added products of pulses, cereals, and nutri-cereals will create a large niche market. AI and Sensor-based technologies, automation, and mechanized farming will prevail. Small and marginal farmers and subsistence farming may come to the brink of extinction. Agriculture will attract greater investments from the private sector. Individual entrepreneurs, agri-based startups, and large farmers will dominate the agriculture sector of the country. Farming will be seen as a valued and profitable business proposition with opportunities for growth and learning. The aware and qualified farm businessmen who will dominate the farming sector will actively seek quality extension and advisory services. Payment-based extension and advisory services, provided by specialized private agencies, individual start-ups, and private extension agents, will crop up as lucrative business ideas. Paid extension, complementary extension, and advisory services will be taken up as an integral part of the product-selling strategy by the private input dealers. Agri-insurance ventures will make headways, and as an important strategy to save insurance coverage, they will hire efficient extension professionals and collaborate with extension service providers to issue quality advice, thus minimizing the risk of crop failures in the farmer's fields.

In this scenario, the entire public extension should undergo metamorphosis to justify its presence, relevance, and public investment. The public extension network, pivoted by the Krishi Vigyan Kendra (KVKs) may reduce investment and manpower recruitment. However, a huge investment will be required for operational efficiencies of the KVKs in the direction of a digitally driven, futuristic extension. The present technology application, demonstration, and capacity-building mode may become obsolete in the scenario of a lesser requirement for technology popularization and top-down technology transfer. Since it is expected that the farming population will become much smaller in size, and that too dominated by aware, educated, and agri-business-minded individuals, the KVKs will face tough competition from the private extension agencies alike, formed to provide paid extension services in line with the situation. Therefore, for the sustained functioning of KVKs, huge investments will be required for the holistic transformation of the Kendras, competent manpower and a technology-driven support system for precise guidance to the clients.

The scope for agro-advisory, participatory agri-business planning, and growth monitoring and evaluation through paid extension professionals will boom. Extension professionals' role expectations will, however, thoroughly change from group and mass communication, technology popularization, and free-of-cost capacity building to demand-driven and client-based extension service provision. Start-ups with the idea of fee-based extension services may crop up as an important business option for agricultural science graduates. Extension professionals equipped with advanced agro-meteorological analytical skills, market intelligence, and AI tools will occupy greater space in the job market. Commensurate with the skill-set demands, the Extension Education Curricula both at the undergraduate and post-graduate levels will require to undergo massive alterations, revisions, and reforms. The Extension Syllabus will require embracing digital agriculture through core competency building in the areas of information communication technology, computer application, psychometry, and resource use efficiency.

The mode and content of teaching Extension Education will demand a paradigm shift from case-oriented and anecdote-based subjective descriptions to method-oriented, skill-based teaching-learning. Product development for more of acting as a facilitator and support system, e.g., customized software development for fulfilling clients' marketing needs, designing sensor-based fertigation control devices, customized hydroponic and aquaponics systems for small areas, etc., will be demanded from the future extension professionals. Language programming, including statistical language programming, data mining, big data analysis, machine learning, and artificial intelligence, will undoubtedly draw attention in Extension curricula re-designing.

India has several global commitments for the future. Government subsidy schemes may be diverted to more innovative approaches to the sustainable intensification of agriculture. Extension professionals need to keep pace with changing innovation and knowledge to meet the future goal of making India a developed nation.

5. References

Antholt, C. H. (1994). Getting ready for the twenty-first century: Technical change and institutional modernization in agriculture (World Bank Technical Paper No. 217). Washington, DC: The World Bank.

Axinn, G. H. (1988). Guide on alternative extension approaches. Rome: Food and Agriculture Organization of the United Nations.

Bhattacharyya, S., Roy Burman, R., Sharma, J. P., Padaria, R. N., Paul, S., & Singh, A. K. (2018). Model villages led rural development: A review of conceptual framework and development indicators. Journal of Community Mobilization and Sustainable Development, 13(3), 513–526.

Food and Agriculture Organization. (2014). Designing nutrition-sensitive agriculture investments: Checklist and guidance for program formulation. Rome: FAO.

Gulati, A., Sharma, P., Samantara, A., & Terway, P. (2018). Agricultural extension system in India: Review of current status, trends and the way forward. New Delhi: ICRIER.

Joshi, P. K., Kumar, P., & Parappurathu, S. (2015). Public investment in agricultural research and extension in India. European Journal of Development Research, 27(3), 438–445. http://dx.doi.org/10.1057/ejdr.2015.36

Kadiyala, S., Harris, J., Headey, D., Yosef, S., & Gillespie, S. (2014). Agriculture and nutrition in India: Mapping evidence to pathways. Annals of the New York Academy of Sciences, 1331(1), 43–56. https://doi.org/10.1111/nyas.12477

Kokate, K. D., Dubey, S., Sah, U., & Paul, S. (2016). Tools, policies and practices in farm technology delivery system: A review. International Journal of Current Research, 8(5), 31438–31445.

Kumar, A., Singh, A. K., Saroj, S., Mishra, M. M., & Joshi, P. K. (2019). The impact of India's Farm Science Centers (Krishi Vigyan Kendras) on farm households' economic welfare: Evidence from a national farmers survey (IFPRI Discussion Paper 01832).

Mahapatra, A., Nikam, V., Paul, S., Ray, M., & Mahra, G. S. (2022). A functional analysis of extension and advisory services offered by farmer producer organization in tribal region of Odisha. Journal of Community Mobilization and Sustainable Development, 17(3), 711–717.

Paul, S., Pradhan, A. K., Srivastava, S. K., Mishra, S. K., & Kumar, G. A. K. (2022). Role of women in ensuring food and nutrition security. Vigyan Varta, 3(4), 140–145.

Paul, S., Vellaichamy, S., Satyapriya, & Singh, P. (2018). Nutritional security vis-à-vis food production in India: The strength of agri-nutri linkage in retrospect. Current Science, 114(3), 439–441.

Roy Burman, R., Paul, S., Sharma, J. P., Padaria, R. N., Singh, R., & Singh, A. K. (2021). Reaching the unreached through designing and validating an innovative extension model: The IARI-Post Office Linkage Extension Model. In S. Dhar, S. Babu, R. R. Subhash, P. K. Upadhyay, T. Singh, S. K. Yadav et al. (Eds.), Extended Summaries of 5th International Agronomy Congress (Vol. 4, pp. 2188–2189). New Delhi: The Indian Society of Agronomy, IARI.

Sangeetha, V., Singh, P., Satyapriya, Lenin, V., Paul, S., & Singh, S. (2018). Value chain for small holder farmers in agri-nutri aspects. Agriculture World, June, 64–70.

Sangeetha, V., Venkatesh, P., Singh, P., Satyapriya, Lenin, V., Paul, S., Mahara, G. S., Muralikrishnan, L., Barua, S., Sitaram, Singh, T., Dubey, S. K., & Yadav, M. (2019). Dietary diversity: Determinants and its relationship with nutritional outcomes in Uttar Pradesh. Indian Journal of Agricultural Economics, 74(3), 444–460.

Satyapriya, Singh, P., Sangeetha, V., Lenin, V., Paul, S., & Barua, S. (2018). Video led learning for agri-nutrition education: A participatory assessment. Indian Journal of Extension Education, 53(1), 60–65.

Srivastava, S. K., Kolady, D., & Paul, S. (2023). Changing food consumption pattern and its implications on achieving zero hunger in India (SDG-2). In S. A. Narula & S. P. Raj (Eds.), Sustainable food value chain development (pp. 131–145). Springer. https://doi.org/10.1007/978-981-19-6454-1_9

Swanson, B. E., Bentz, R. P., & Sofranko, A. J. (Eds.). (1997). Improving agricultural extension: A reference manual (3rd ed.). Rome: Food and Agriculture Organization of the United Nations.

14 Agricultural Policy

Pratap S. Birthal[1]

1. Context

Technologies and innovations in and for agriculture, supported by massive investments in irrigation, infrastructure (e.g., roads, power, communication, and markets), institutions (e.g., agricultural extension and rural credit), and incentives (e.g., input subsidies and output price support), have propelled India into food self-sufficiency and even a significant exporter of some commodities like rice. Nevertheless, the need to produce more food remains as urgent as ever. By 2047 — the centenary year of its independence — the population is projected to reach 1.6 billion. Close to half of the population will live in cities and towns. More importantly, India is envisioned to be among the league of developed countries by that time, which means the economic growth will need to accelerate to about 8% per annum from 6.4% realized during the past decade.

These economic and demographic changes will significantly shift dietary patterns and food demand. By 2047, overall food demand will grow at an annual rate of about 3% (NITI Aayog, 2024). The demand for nutrient-dense food commodities, such as vegetables, fruits, milk, meat, fish, and eggs, will grow much faster, at over 5% per annum, compared to an annual growth of 1.7% in demand for foodgrains.

The agri-food production systems, on the other hand, will face several biotic and abiotic challenges, including the growing scarcity of land, water and energy, increasing threats of climate change, and loss of biodiversity. Due to its growing uses for residential and industrial purposes, the arable land has declined from 189.6 million hectares (Mha) in 1950-51 to 180.1 Mha in 2021-22. The net cropped area has stagnated at around 140 Mha for the past two decades. Further, about two-thirds of the arable

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land suffers from one or another form of degradation. This implies there is little scope for bringing additional land under cultivation.

The growing water scarcity will severely constrain the intensification of existing cropland. The annual per capita availability of water has declined drastically from 5178 m^3 in 1951 to 1486 m^3 in 2021, which is 13% below the norm of 1700 m^3. By 2050, the per capita water availability is projected to fall even further below the norm. Of the available 1097 billion cubic meters (BCM) of freshwater, over 85% is used for agriculture.

In plausible future scenarios, the frequency of extreme climatic events such as droughts, floods and heatwaves will increase, causing significant damage to the sustainable development of agriculture and agriculture-based livelihoods. It may be noted that during the past four decades, climate risks have reduced the productivity growth of Indian agriculture by 25% despite technical progress and expansion of irrigation, contributing to improvements in productivity and resilience.

Agriculture, besides being a source of food, feed, fibre, and fuel, is still the primary source of income and livelihood for 45% of the population, despite a significant decline in its share of the gross domestic product to 18% in 2022-23 from over 50% during the 1960s. Smallholders dominate Indian agriculture. The average landholding size has shrunk to 1.08 hectares in 2016 from over 2 hectares in the early 1970s. Approximately 70% of farm households cultivate tiny pieces of land that do not exceed one hectare. Their proportion will increase further, restricting scale economies and income and employment opportunities in agriculture.

Nevertheless, given its crucial role in the nation's food security and farmers' livelihood, agriculture will remain at the center of India's economic development policies. However, agricultural policies and programs should be aligned to the emerging structural changes in the agricultural sector and the challenges and opportunities in the domestic and international markets to achieve the sustainable transformation of agriculture.

2. Goals of Agricultural Policy

India's agricultural policy has evolved to address the challenges of food insecurity. It has succeeded in its intended objective. However, given the emerging challenges to agriculture, the future roadmap should envision a holistic and integrated approach to agricultural development that ensures the country's food security, improves its resilience to climate and other shocks, preserves biodiversity and environment and enhances farmers' incomes and livelihoods.

The policy should be built upon three fundamental principles to ensure a robust pathway for agricultural development. These are:

- ***Efficiency***: The policy intervention should improve production efficiency, i.e., higher productivity and lower production costs. This can be achieved by adopting new technologies and agronomic practices, optimizing resource use, improving the efficiency of fixed and variable inputs, and improving the entrepreneurial skills of the farming communities.
- ***Inclusiveness*:** The policy should aim to improve the economic and social outcomes (income, inequality, poverty, and malnutrition) for the people intended to be beneficiaries without compromising the welfare of others. It should be scale-neutral to benefit all and reduce inter-personal, intra-, and inter-regional disparities.
- ***Sustainability*:** The policy interventions should support the goals of efficiency and inclusiveness without risking the health of natural resources and inter-generational equity.

Yet, there are a few challenges in adhering to these basic principles:

- ***Trade-offs***: The possibility of tradeoffs among policy goals cannot be ignored. It is uncertain whether a policy that aims to improve efficiency would adversely affect the sustainability of natural resources or vice versa. For instance, the subsidies for irrigation/ electricity and agro-chemicals aimed at enhancing food production, if continued for long, may be detrimental to the sustainability of land and water resources, biodiversity, and the environment. Therefore, policies should be revisited periodically and reformed to align with emerging economic and environmental challenges and market opportunities.
- ***Crowding-out effects***: Policies are often guided by the electoral manifesto of the political party in power. Thus, there is a high probability of providing freebies or subsidies to seek electoral support. This is because the benefits from subsidies are immediately visible, while investment pays in the long run. Hence, subsidies may crowd out investment. Policies should, therefore, be devised to lead to better outcomes while fulfilling the political agenda of the government in power.
- ***Stakeholders' engagement in policy formulation***: Policy formulation should not be based on subjective assessments of its

uptake and outcomes. It should be based on empirical evidence and the experiences of stakeholders, including the farmer organizations, civil society, and relevant industries, in setting the targets. This will avoid over-optimism of a policy. Further, as no size fits all, it is essential to devise regionally differentiated strategies, considering the resource endowments and requirements of the farming communities.

- ***Policy coherence*:** Policies formulated and implemented in isolation with other similar objectives are unlikely to yield better outcomes. To ensure cost-effective implementation and better outcomes, harnessing the synergy between agricultural, environmental, health, and trade policies is essential.

3. Policy Roadmap

3.1. Investment priorities

Investment priorities depend on the availability of financial and human resources, as well as challenges and opportunities in different segments of agriculture. Hence, investment priorities should be decided based on efficiency, sustainability, and inclusiveness goals.

3.2. Sub-sector allocation of resources

In its endeavor to achieve self-sufficiency in staple foods, India's agricultural policy has mainly focused on crops. Animal husbandry and fisheries have emerged as the main drivers of agricultural growth in recent years. Significantly, these activities are concentrated among smallholders and are more remunerative than most crops; hence, they significantly affect equity and poverty. Nonetheless, their shares in investment have remained much less than their economic contribution or even have declined. For instance, livestock contributes about one-third to the agricultural gross domestic product (Ag GDP) but receives only about 11% of the total investment in the agricultural sector.

India has a huge population of different livestock species, but low productivity because of scarcity of feed and fodder, frequent outbreaks of diseases, and poor breeding and health infrastructure. Therefore, emphasis should be placed on optimizing the livestock population (especially cattle), managing diseases, and augmenting feed and fodder supplies. The declining utility of male cattle as draught animals suggests the need for the promotion of sex-sorted semen technology. Large-scale prophylactic vaccination of animals against important diseases is essential for reducing production losses and improving animal health. It is, therefore, important to revisit investment priorities regularly, realigning them with the growth potential of different segments and their likely economic, social and environmental outcomes.

3.3. Management of Natural Resources

Land, water and energy are the key factors in agricultural production. These are scarce and have been facing quantitative and qualitative deterioration. Their deterioration may continue in the absence of appropriate management strategies.

3.4. Water management

The efficiency of flood irrigation, the most widely used method, does not exceed 35%. Therefore, the policy should promote pressurized irrigation systems like drip and sprinkler systems that significantly enhance water-use efficiency, avoid wastage of water, reduce the cost of irrigation and other inputs, and contribute to higher crop yields. Micro-irrigation should be bundled with automation (irrigation scheduling sensors) and solar power for better economic and environmental outcomes. Further, there is an urgent need to rejuvenate canal irrigation and promote conjunctive use of water.

3.5. Land-use planning and soil fertility

Soils matter in deciding the cropping pattern, adoption of conservation practices, and nutrient use. The need for land-use planning at a granular scale (block level) cannot be undermined. Hence, there is a need to establish a nationwide soil health monitoring system for preserving soil quality and deciding cropping patterns and fertilizer use.

Resource-endowment-based crop planning is necessary but not sufficient for sustainable development in agriculture. Hence, resource-based planning should be accompanied by economic incentives for farmers to adopt recommended cropping patterns, technologies, and agricultural practices.

India provides fertilizer subsidies worth Rs 2.5 billion, resulting in indiscriminate and unbalanced use of nutrients. Linking fertilizer subsidies to the recommendations in the soil health cards will lead to the balanced use of different fertilizers, improved soil health, and possibly resilience of agriculture against climate change.

Approximately 86% of landholdings are smaller than or equal to one hectare. These have been fragmenting or dividing, restricting scale economies. To realize scale economies, it is essential to consolidate such holdings through institutional arrangements such as cooperatives and farmer-producer organizations or through voluntary land consolidation to form larger, more economically viable plots. The government may offer financial incentives or subsidies to farmers who consolidate their landholdings. The other option is to implement secure land leasing models that allow smallholders to lease their land to larger farmers.

3.6. Renewable energy

Agriculture heavily depends on electricity and diesel to meet energy requirements. Given the limited scope for further exploitation of fossil fuels, it is crucial to transit towards renewable energy sources like solar and wind. Farmers can be incentivized to switch to these sources. Bioenergy from agricultural wastes like crop residues and dung is also equally important. In the latter case, it is essential to make it competitive in relation to electricity and diesel.

3.7. Precision agriculture

The application of remote sensing, GPS, drones, and sensors will aid in deciding the optimal use of natural resources and, thus, better farm outcomes in terms of productivity and resilience.

4. Climate Risk Management

The frequency of extreme climatic events like droughts, floods and heatwaves is predicted to increase, causing significant damage to agriculture and agriculture-based livelihoods in the absence of ameliorative measures.

4.1. Climate-smart practices

Promote climate-smart agricultural practices, including stress-tolerant crop varieties and integrated nutrient management that reduce greenhouse gas emissions and enhance crop resilience. Encourage the application of bundled technological and agronomic interventions for better outcomes.

4.2. Forewarning and advisory system

A significant proportion of climate-induced loss in agricultural production can be avoided if farmers are provided weather advisories well in advance. Hence, strengthening forewarning systems for the generation of quality weather advisories, their digitization and dissemination is essential to help farmers make informed decisions to manage climate-related risks to agriculture.

4.3. Crop insurance

Crop insurance, a mechanism to transfer risk from farmers to financial agencies against payment of a fee or premium, also influences farmers' decisions regarding input use, hence agricultural productivity and farmers' incomes. One size does not fit all farmers and regions. However, only about 35% of the gross cropped area is covered by crop insurance. There is a need for a more comprehensive consultation regarding issues of its poor coverage and, accordingly, evolving crop-, farm—and region-specific insurance strategies.

4.4. Climate finance

Finance is one of the main limitations to improving the productivity and resilience of smallholder agriculture. However, agricultural credit policy has primarily targeted productivity enhancement, with little consideration for risk reduction. Given the rapid climate changes, it is imperative to make climate finance an integral component of investment planning for agriculture and rural development.

5. Agricultural R&D

Agricultural research can address multiple challenges. Hence, investment in agricultural research made today will shape the future trajectory of agricultural growth and its social, economic and environmental outcomes.

5.1. Investment

In 2020-21, India invested 0.49% of agricultural gross domestic product in agricultural research, not even half the global average of about 1%. Research has significant potential to contribute to the sustainable development of agriculture and, consequently, its economic and social outcomes. It is, therefore, imperative to enhance public funding of agricultural research.

5.2. Research agenda

India's agricultural research system primarily focuses on enhancing productivity. India is self-sufficient in several food commodities. Hence, the focus of research needs to be shifted towards improving the resilience of agriculture, preserving natural resources, biodiversity, and the environment, and improving the nutritional quality of food.

5.3. Balance resource allocation

The bulk of investment goes for crop science research, while animal husbandry and horticulture, which have been driving agricultural growth, remain underfunded. It is, therefore, essential to revisit commodity research priorities and balance the allocation of research resources.

5.4. Public-private partnership

Agricultural research is funded largely by the budgets of central and state governments. Private-sector investment is meagre. Nonetheless, the significant size of the agricultural sector and the emerging challenges and opportunities present considerable scope for public-private partnerships in agricultural research. A clear policy framework that encourages public-private partnership in agricultural R&D, including tax incentives, subsidies, and grants for private investments in research. Simplify regulations to make it easier for private companies to collaborate with public research institutions. Create innovation hubs or research parks where public and private sectors can collaborate, share knowledge, and access shared facilities and resources. Strengthen the collaboration between public extension services and private companies to ensure that new technologies are effectively transferred to farmers.

6. Payment for Ecosystem Services (PES)

Ecosystem services are the benefits people receive from nature. Several agricultural practices, such as agroforestry, no-till farming, integrated nutrient management, crop rotations, cover crops, etc., generate intangible ecosystem services (e.g., carbon sequestration, nitrogen fixation, climate regulation, water saving, etc.) that remain unvalued or undervalued.

6.1. Prioritization and monetization

Identify and prioritize agricultural practices that generate ecosystem services (e.g., carbon sequestration, nitrogen fixation, climate regulation, water saving, etc.) and assess their economic worth to compensate farmers for their contribution to the environment and human health.

6.2. System for certification and payment

Develop a system for certification and payment of ecosystem services. This may also include market-based tradable credits for carbon sequestration and biodiversity.

6.3. Repurposing subsidies

India spends hugely on fertilizer and electricity subsidies. These incentives have become detrimental to the health of natural resources. It is time that these subsidies are repurposed to adopt sustainable farming practices that generate ecosystem services, mitigate greenhouse gas emissions, improve the health of natural resources, and preserve biodiversity and the environment.

6.4. Private sector participation

The industrial sector is the primary source of greenhouse gas emissions. Hence, private investment in PES should be encouraged as part of their corporate social responsibility (CSR).

7. Institutions

Institutions act as bridges between farming communities, other stakeholders on the value chain, and policymakers to improve productivity and resilience and reduce costs associated with the production and marketing of agricultural commodities.

7.1. Farmers' collectives

Strengthen cooperatives and farmer-producer organizations (FPOs) to improve farmers' bargaining power and access to domestic and international markets. Farmers' collectives are also essential for managing natural resources such as land and water.

7.2. Extension system

Farmers' information needs are varied and are likely to increase significantly to realign agriculture with emerging challenges and opportunities. However, nearly half of the farm households do not have access to information and depend on informal sources. Hence, there is a need to strengthen the public extension system to assist farmers with technical and financial planning for better farm outcomes.

7.3. Credit

Farmers, especially smallholders, face liquidity constraints in adopting improved agricultural practices. Hence, there is a need to enhance smallholder farmers' access to institutional credit, especially for activities such as animal husbandry and horticulture that are concentrated among smallholders and provide more returns compared to widely grown staple food crops.

8. Markets and Value Chains

Markets act as a catalyst in agricultural development. Underdeveloped markets result in higher transaction costs and lower price realization. In India, growth in agricultural markets has not kept pace with growth in agricultural production. Value chains for most commodities have also not been developed.

8.1. Market linkages

Strengthen linkages between producers, processors, and markets through collectives and contracts to improve the efficiency and inclusiveness of supply chains.

8.2. Processing and value addition

Provide financial support to farmers' collectives such as cooperatives, FPOs, startups, and MSMEs for processing, packaging and branding to add value to primary agricultural produce.

8.3. Infrastructure

Invest in cold storage, warehouses, and refrigerated transportation to reduce post-harvest losses of perishable goods.

8.4. Food safety and quality

Develop traceability systems to ensure transparency, quality and safety of food products from farm to fork.

8.5. Market intelligence

Develop a market and trade intelligence system to explore new export markets, simplify trade procedures, and reduce barriers to the export of agricultural products.

8.6. Agri-export zones

Establish dedicated agri-export zones for niche commodities with facilities like quality testing labs and packaging units to meet international standards.

8.7. Prices

Promote transparency in pricing mechanisms to ensure that small farmers receive a fair price. Establish price stabilization funds or guarantee minimum prices for key export crops to protect small farmers from global price fluctuations.

8.8. Crop-neutral price policy

Evolve a price policy that does not distort markets and promotes a balanced cropping pattern suited to the local resource endowments.

9. Empowerment of Farm Women

Women play an important role in agriculture and are custodians of household food and nutrition security. They are more productive than their male counterparts.

9.1. Reduce drudgery

Investment in research and development for technologies and practices that reduce drudgery for women farmers.

9.2. Property rights

Ensure property rights to women and enhance their access to credit, information, extension systems, and government-run agricultural schemes to enable them to adopt improved technologies and practices.

9.3. Training

Women farmers are trained in modern farming techniques, sustainable practices, digital agriculture, agribusiness management, and marketing and food safety.

10. Food Security and Nutrition

Over 10% of the Indian population is food and nutrition insecure because of a lack of economic access to food.

10.1. Diversify into high-value and biofortified crops

Promote the cultivation of various crops, especially high-value and biofortified crops, for their nutrition and therapeutic values and to enhance food and nutritional security.

10.2. Price stabilization

Strengthen policy and institutional measures to stabilize food prices and ensure affordability.

10.3. Nutrition education

Promote formal and informal nutrition education to encourage healthy eating habits and reduce the consumption of ultra-processed foods.

10.4. Food waste and loss

Investment in post-harvest infrastructure (i.e., storage, warehousing, refrigerated transport and packaging to reduce food loss, especially in perishable commodities. Equally important is creating mass awareness about food waste and encouraging responsible consumption behaviors.

11. Rural Non-farm Sector

Agriculture is dominated by small landholdings, employing about 45% of the workforce. Given occupation choices in the non-agricultural sector, over 40% of farmers are willing to quit agriculture.

11.1. Rural industrialization

If the income constraint due to ubiquitous smallholdings were to be mitigated, then the need to accelerate the pace of rural industrialization should not be undermined. The expanding rural sector will create employment opportunities for rural youth in ancillary industries related to inputs, equipment, machines and services and reduce employment pressure on agriculture. Invest in rural infrastructure such as healthcare, education, and housing to improve the quality of life in rural areas, making them more attractive to live and work in.

11.2. Skill development

Promote vocational training in rural industrialization and establish innovation hubs in rural areas that support agricultural startups and rural industries. Facilitate access to low-interest loans and credit for young farmers, ensuring they have the financial support to invest in rural non-farm enterprises.

12. Governance and Policy Coherence

Governance and policy coherence are crucial to effective public administration and policy implementation. They involve aligning and coordinating policies across different sectors and governance levels.

12.1. Stakeholder engagement

Develop comprehensive policy frameworks aligning sectoral policies with national development goals by involving diverse stakeholders, including farmers, consumers, civil society organizations, and industry leaders, in policy development and implementation.

12.2. Coordination mechanisms

Establish mechanisms to ensure coordination and synergy between agricultural, environmental, health, and trade policies to promote coherence and synergy for inclusive and sustainable agri-food systems.

12.3. Monitoring and evaluation

Establish robust monitoring and evaluation systems for fixing implementation responsibilities across sectors, assessing policy impacts, and identifying and addressing inconsistencies.

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Summary and Way Forward

P.K. Joshi[1]

1. Context

As India celebrates its hundred years of independence in 2047, the aspiration to become a developed nation requires visionary changes and transformative actions across all sectors of the economy. Agriculture, which sustains over half of the Indian population, has the potential to emerge not just as a means of livelihood but should evolve into a driving force of innovation, economic strength, and environmental protection. The role of agricultural research, education, and extension will be pivotal in achieving this transformation.

The trajectory of Indian agriculture from food-deficient to food-self-sufficient and exporter has been unprecedented. However, there are numerous challenges in the future. Important ones are resilience to climate change, sustainable intensification, remunerative markets, global competitiveness, and equitable prosperity. Agricultural research should deliver next-generation solutions; education should cultivate visionary leaders; and extension should ensure no farmer is left behind.

2. Agricultural Research: Innovating for Resilience and Prosperity

Agricultural research should evolve dynamically to address the challenges foreseen in the next twenty-two years. Future research priorities should focus on:

- ***Genomics and Biotechnology***: Genomic selection, gene editing (CRISPR technology), and bio-stimulants can usher in a new green revolution.

[1] National Academy of Agricultural Sciences, New Delhi.

- ***Climate-Resilient Agriculture***: Crop varieties tolerant to drought, salinity, floods, and extreme temperatures should be developed. For example, the recent success of drought-tolerant rice varieties and salt-tolerant wheat should be scaled up.
- ***Precision and Digital Agriculture***: Leveraging drones, IoT sensors, AI models, and satellite imagery can revolutionize farm productivity and resource management.
- ***Sustainable Resource Management***: Research should focus on soil rejuvenation, water conservation technologies (like micro-irrigation and rainwater harvesting), and regenerative agricultural practices.
- ***Strengthen high-value commodities*:** Harnessing the potential of the horticulture, animal, and fisheries sectors will accelerate agricultural growth, generate employment, and empower youth and women.
- ***Need-based farm mechanization and agro-processing***: Developing automated farm machinery which can enhance agricultural productivity, reduce labor dependency and ensure efficient use of resources. Promoting agro-processing would add value to farm produce, boost rural employment and strengthen the agro-economy.
- ***Reform agricultural policies and evolve innovative institutions***: Reforming agricultural policies, modernizing agri-infrastructure, and improving market access will empower farmers and boost their income. Evolving innovative institutions that focus on agri-tech, cooperatives, farmer producer organizations and sustainable practices will drive productivity and contribute significantly to rural prosperity.
- ***Agri-Value Chain and Post-Harvest Research***: Storage, processing, and marketing innovations can drastically reduce post-harvest losses and increase farmers' incomes.

Strengthening India's National Agricultural Research System (NARS) by promoting interdisciplinary and transdisciplinary collaborations and ensuring greater private sector participation in agri-research will be critical to making India a developed nation. International partnerships with global institutions will help in technology transfer, capacity building, and benchmarking against best practices.

3. Agricultural Education: Shaping Leaders for The New Era

Agricultural education should move beyond conventional frameworks to embrace a holistic and futuristic vision. Indian agricultural universities need a paradigm shift in their approach as per the National Education Policy:

- ***Curriculum Modernization***: Courses should be updated to include topics like Artificial Intelligence in agriculture, agri-entrepreneurship, climate-smart farming, organic and natural farming, agribusiness management, and agricultural export strategies.
- ***Experiential Learning***: "Learning by doing" should become the core pedagogical principle. Students should work on real-life problems through internships, village adoption programs, hackathons, and startup incubation.
- ***Skill Development and Capacity Building***: Short-term certificate programs and vocational training should be offered to rural youth and women, encouraging grassroots innovation and entrepreneurship.
- ***Promoting Innovation and Startups***: Agri-incubators and innovation hubs within universities can nurture student-led startups focusing on farm machinery, food processing, bio-inputs, and climate-smart tools.
- ***Internationalization***: Partnerships with international universities and participation in global research networks can expose students to the latest trends and technologies, ensuring a world-class education.

Agricultural education should also emphasize sustainability, inclusiveness, and ethical responsibility. It should prepare students to become change agents—not just in terms of productivity but also of rural transformation, equity, and environmental stewardship.

4. Agricultural Extension: Disseminating Knowledge and Technology

Agricultural extension, the crucial link between research organizations and farmers' fields, needs drastic strengthening and modernization.

- ***Digital Empowerment***: Extension services should harness mobile apps, farmer helplines, online advisory platforms, WhatsApp groups, and YouTube tutorials to reach millions of farmers quickly and effectively.

- ***Customized and Localized Advisory Services***: Region-specific, crop-specific, and farmer-centric advisories will ensure higher adoption of technologies and best practices.
- ***Strengthening Farmer Producer Organizations (FPOs)***: FPOS should be nurtured as marketing collectives and hubs of knowledge dissemination, technology adoption, and agribusiness ventures.
- ***Participatory Extension Models***: Moving from top-down to bottom-up approaches, where farmers are seen as partners and innovators, will increase ownership and success.
- ***Gender-Sensitive Extension***: Extension programs should deliberately target women farmers, recognizing their critical but often invisible role in Indian agriculture.
- ***Reform Krishi Vigyan Kendras***: Modernizing Krishi Vigyan Kendras is necessary by integrating them with advanced agri-tech, data-driven advisory services, and climate-resilient practices to empower farmers with real-time solutions. Strengthening Krishi Vigyan Kendras as hubs for innovation, skill development, and farmer-scientist collaboration will enhance agricultural productivity and sustainability.

Public-private partnerships (PPP) models, involvement of NGOs and collaboration with rural startups can create a vibrant and pluralistic extension system. Demonstrations of successful models, such as *e-Choupal, Mahendra Samriddhi* Centers, *Shakti* Initiative and Digital Green, should be scaled up and adapted.

The inclusion of feedback mechanisms where farmers can rate and review advisory services should be made mandatory, which will ensure accountability and continuous improvement.

5. Epilogue

India can unlock its vast potential in agriculture by strategically investing in agricultural research, education, and extension. The vision for 2047 is to completely transform Indian agriculture and make it knowledge-driven, technology-intensive, globally competitive, environmentally sustainable, and socially inclusive.

A developed India will be one where every farmer has access to the best of science and technology, rural youth aspire to be agri-entrepreneurs, innovation flourishes from village clusters, and agriculture becomes a proud, profitable, and prestigious profession.

Through collective will, visionary leadership, and strategic action, Indian agriculture has the potential to make India a developed and prosperous nation by 2047.

About the Book

The book emphasizes transforming agriculture as a driver of innovation, economic growth, and environmental sustainability. It also stresses the critical role of agricultural research, education, and extension in achieving the goal of a developed India. It proposes that the research must focus on genomics, biotechnology, diversification towards livestock, horticulture and fisheries, digital agriculture, circular agricultural economy, food-energy-water nexus, climate change, natural resource management, farm mechanization, and agri-value chains to boost productivity, sustainability, and resilience. Educational reforms should include modernizing curricula, promoting experiential learning, nurturing entrepreneurship, and building global partnerships to create visionary leaders. Strengthening agricultural extension is vital, using digital tools, farmer-centric advisories, participatory models, and gender-sensitive approaches. Revamping *Krishi Vigyan Kendras* and fostering public-private partnerships will ensure no farmer is left behind. By aligning policies, institutions, and innovations, India can build a knowledge-driven, competitive, and sustainable agricultural sector, positioning itself as a developed nation where agriculture is a proud, profitable, and prestigious profession. Through collective will, visionary leadership, and strategic action, agriculture has the potential to make India a developed nation by 2047.

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