NITI Aayog

SCENARIOS TOWARDS VIKSIT BHARAT AND NET ZERO

SECTORAL INSIGHTS: AGRICULTURE

(VOL. 6)

सत्यमेव जयते

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FOREWORD

It is widely felt that India's next agricultural transition must move beyond the Green Revolution paradigm. While that model once addressed severe food shortages faced by the country and delivered self-sufficiency and even surplus in cereals, it is no longer equipped to meet the expected outcomes from the sector. Today, expecting the same approach to deliver on multiple fronts, such as food and nutritional security, healthy diets, decent livelihood for nearly half of the population dependent on agriculture, sustainable use of natural resources, and resilience to growing climate and economic shocks, is neither fair nor feasible. The challenge now is to define how we transition in a way that delivers these multiple outcomes. However, the pathways to transition to achieve new outcomes are not sufficiently explored. As the country advances toward achieving the twin objectives of Viksit Bharat and net-zero by 2070, the need to develop new pathways focused on growth in output, accelerated farmers income, sustainable use of natural resources and environment friendly and climate smart agriculture production assumes crucial importance.

We present to you this timely report, which offers a blueprint to reimagine the role of agriculture as central to sustainable growth, farmers' livelihood, food and nutritional security, and climate resilience, while leveraging mitigation co-benefits. Conceived under NITI Aayog's **multi-ministerial Working Group on Agriculture**, the report outlines **India's first long-term pathways for the sector**, with an estimated **~25% mitigation co-benefits by scaling existing policy-led interventions by 2070**. These first-of-its-kind estimates are grounded in the future trajectories designed by key stakeholders for the policy-led interventions. The four central interventions —crop diversification, improved animal nutrition and health, fertilizer use optimization, and the scaling up of chemical-free farming practices—together form a practical basket of high-leverage policy-driven strategies aligned with India's broader priorities for agriculture.

Three features make this analysis particularly relevant for policy action. First, its long-term horizon—spanning 2030, 2047 to 2070—offers governments at all levels a forward-looking planning compass. Second, its pathways emerged from a collaborative process involving policy makers from key ministries and researchers from various ICAR institutions and civil societies, ensuring convergence on what is both desirable and feasible. Third, the report supposes that an integration of food systems approach could hold an untapped potential to unlock deeper mitigation and other co-benefits.

While this is a first-of-its-kind effort, it must be seen as a starting point. The scope for refinement is significant with the integration of a food systems approach that connects supply-side interventions with shifts in human consumption, and other demand (feed, fibre, bio-based economy and waste). As a result, the pathways must evolve to estimate impacts beyond mitigation co-benefits to understand long-term impacts on trade, land use, food and nutritional security, and livelihoods. However, this makes the direction clear: integrating climate ambition with agricultural development is not only possible—it is necessary.

I congratulate the Green Transition, Climate and Environment team of NITI Aayog, the Council on Energy, Environment and Water (CEEW), and all the members of the Working Group for this unique contribution. I do hope that the insights presented in the report and its call to action guide us in crafting an agri-food system transformation that is resilient and planet-positive, worthy of both current citizens and generations yet unborn.

[Ramesh Chand]

Place: New Delhi
Date: January 21, 2026

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FOREWORD

India's Agriculture and Allied sectors remain the backbone of the economy, contributing about one-fifth of the country's GVA and employing nearly 46% of the workforce. The sector ensures food and nutritional security while increasingly supporting value chains and clean energy. India is the world's largest milk producer and sustains rural livelihoods, enabling co-products such as fodder, organic fertilizer and biogas. The country is also a leading producer of millets - the climate-resilient, water-efficient and nutrient-rich cereals - being promoted through various government programs. Agriculture also supplies key biofuel feedstocks for meeting ethanol blending targets.

The agriculture sector is also facing the impacts of the climate change. Rising temperatures, altered rainfall patterns, and increasing frequency of extreme weather events are undermining agricultural productivity and affecting farmers' incomes and food security. Agriculture also accounts for a share of India's greenhouse gases (GHGs) emissions, mainly from livestock and rice cultivation, fertilized soils and manure, and from energy use in farm machinery and irrigation.

NITI Aayog has conducted a detailed study to design long-term, evidence-driven pathways to understand agriculture's role in India's pathways to net zero. The focus is to identify options that enhance national agricultural yield, support farmers' income, improve food and nutritional security and make the sector climate-resilient, with mitigation as a co-benefit.

This analysis highlights the instrumental role of sustainable and climate-smart rice cultivation practices. Overall, the study's findings demonstrate the potential to enhance national agricultural productivity, strengthen farmers' incomes, ensure food and nutritional security, and build a climate-resilient agricultural sector.

I am grateful to Prof. Ramesh Chand, Member, NITI Aayog for providing leadership to this working group and for his keen interest in this study. I also thank the knowledge partner CEEW and all members of the Working Group for their contributions. I congratulate NITI colleagues - Dr. Anshu Bharadwaj, Shri Amit Verma, Dr. Priyanka Sarkar, Shri Venugopal Mothkoor, Dr. Anjali Jain and Shri Nitin Bajpai for their work on this excellent report. I am confident that this report will help develop a productive, resilient and sustainable agri-system.

Dated: 5th February, 2026 **[B.V.R. Subrahmanyam]**

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List of Abbreviations

AFOLU	Agriculture, Forestry, and Other Land Use
AIBP	Accelerated Irrigation Benefits Programme
ANN	Artificial Neural Network
APCNF	Andhra Pradesh Community Managed Natural Farming
APY	Area, Production, and Yield
AR5	Fifth Assessment Report
ARIMA	Autoregressive Integrated Moving Average
AWB	Agricultural Waste Burning
AWD	Alternate Wetting and Drying
BGREI	Bringing Green Revolution to Eastern India
BioE3	Biotechnology for Economy, Environment and Employment
BPKP	Bharatiya Prakritik Krishi Paddhati
BRC	Biodiversity Resource Centres
BUR4	Fourth Biennial Update Report
CAGR	Compound Annual Growth Rate
CBG	Compressed Biogas
CDP	Crop Diversification Programme
CGIAR	Consultative Group on International Agricultural Research
CHC	Custom Hiring Centres
CPS	Current Policy Scenario
CRM	Crop Residue Management
CRP	Community Resource Person
DAHD	Department of Animal Husbandry and Dairying
DI	Drip Irrigation
DSR	Direct Seeded Rice
FAI	Fertiliser Association of India
FAO	Food and Agriculture Organization
FPOs	Farmer Producer Organisations
FUE	Fertiliser uptake/use efficiency
GCA	Gross Cropped Area
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GoI	Government of India
GP	Gram Panchayat
GWP	Global Warming Potential

HYV	High-Yielding Varieties
IAM	Integrated Assessment Modelling
ICAR	Indian Council of Agricultural Research
ICDS	Integrated Child Development Services
IGFRI	ICAR-Indian Grassland and Fodder Research Institute
INM	Integrated Nutrient Management
IPCC	Intergovernmental Panel on Climate Change
IVF	In-Vitro Fertilisation
LT-LEDS	Long-Term Low-Carbon Development Strategy
Mha	Million Hectares
MM	Manure Management
MoAFW	Ministry of Agriculture & Farmers' Welfare
MoEFCC	Ministry of Environment, Forest and Climate Change
MT	Million Tonnes
$MtCO_2e$	Millions Tonnes of Carbon Dioxide equivalent
NAAS	National Academy of Agricultural Sciences
NDC	Nationally Determined Contributions
NF	Natural Farming
NFSA	National Food Security Act
NFSM	National Food Security Mission
NICRA	National Innovations in Climate Resilient Agriculture
NITI Aayog	National Institution for Transforming India Aayog
NMM	National Millet Mission
NMNF	National Mission on Natural Farming
NMSA	National Mission for Sustainable Agriculture
NPOP	National Programme for Organic Production
NRLM	National Rural Livelihood Mission
NSA	Net Sown Area
NUE	Nitrogen Use Efficiency
NZS	Net Zero Scenario
OECD	Organisation for Economic Co-operation and Development
PDS	Public Distribution System
PGS	Participatory Guarantee System
PIB	Press Information Bureau
PKVY	Paramparagat Krishi Vikas Yojana
PM POSHAN	Pradhan Mantri Poshan Shakti Nirman
PMDDKY	PM Dhan Dhanya Krishi Yojana
PMGKAY	Pradhan Mantri Garib Kalyan Anna Yojana
PMKSY	Pradhan Mantri Krishi Sinchayee Yojana
PMKSY-MI	Pradhan Mantri Krishi Sinchayee Yojana - Micro Irrigation
PMO	Prime Minister's Office

PM-PRANAM	Programme for Restoration, Awareness Generation, Nourishment, and Amelioration of Mother-Earth
R&D	Research & Development
RBP	Ration Balancing Programme
RKVY	Rashtriya Krishi Vikas Yojana
SATAT	Sustainable Alternative Towards Affordable Transportation
SDG 17	Sustainable Development Goal 17
SHC	Soil Health Card
SHGs	Self-Help Groups
SHM	Soil Health Management
SI	Subsurface Irrigation
SMAM	Sub-Mission on Agricultural Mechanisation
SOC	Soil Organic Carbon
SRC	Sustainable Rice Cultivation
SRI	System of Rice Intensification
SYI	Sustainable Yield Intensification
UN-DESA	United Nations Department of Economic and Social Affairs

Executive Summary

Context and Purpose

Agriculture sits at the complex intersection of India's Viksit Bharat aspirations and its Net Zero ambition. As the anchor of India's rural economy, the sector supports 46% of the workforce and ensures national food security while contributing ~14% to Gross Value Added (GVA) (MoF, 2025). However, this foundational role characterised by the dominance of small and marginal farmers, is increasingly threatened by climate change, soil degradation, and acute water stress.

The sector also faces a dual challenge: it must meet escalating demands for food, fiber, and bio-energy while grappling with a heavy environmental and resource footprint. Agriculture currently accounts for ~14% of national Greenhouse Gas (GHG) emissions, driven by methane from enteric fermentation and rice cultivation and nitrous oxide from agricultural soils (MoEFCC, 2024). Furthermore, the sector consumes ~18% of national electricity (275 TWh) (CEA 2024), primarily to power groundwater irrigation and expanding mechanisation.

Given the structural constrains and socio-economic salience, the sector's long-term planning requires a **differentiated approach that prioritizes adaptation interventions while actively delivering mitigation co-benefits.** Recognising this imperative, NITI Aayog has constituted a multi-ministerial Working Group on the Agriculture Sector. This 42-member inter-disciplinary group operates with the objective:

"To develop and analyse various options/pathways to achieve long-term resilience, farmers' incomes, food and nutritional security that deliver mitigation co-benefits, considering the impacts of technology, policy, investment, ecology-based farming systems, and others."

The Exercise and Scenarios

The study adopts an "adaptation-first" approach, assessing how pathways aimed at improving resilience, farmers income, productivity and resource efficiency can also deliver mitigation co-benefits. This mirrors India's agricultural policy landscape, where initiatives such as the *National Mission on Sustainable Agriculture (NMSA), Crop Diversification Programme (CDP), National Livestock Mission (NLM)* already demonstrate the inherent synergy between adaptation and mitigation outcomes (MoEFCC 2024).

The study applies supply-side modelling to assess long-term mitigation and on-farm energy-efficiency co-benefits of various pathways (Table E.1 & E.2). Using 2019 as the baseline, agricultural production projections for major crops and milk are aligned with NITI Aayog's *"Crop Husbandry, Agriculture Inputs, Demand and Supply"* for 2019–2047 and extrapolated to 2070. Any pathway-induced changes in production are translated into corresponding mitigation co-benefits using IPCC Tier-2 methods and into achieving on-farm energy efficiency. These outcomes are assessed under two stakeholder-driven scenarios: The Current Policy Scenario and an accelerated Net Zero Scenario. The two scenarios capture both existing and accelerated policy adoption through stakeholder-driven assumptions for 2047 and 2070. Tables E.1 and E.2 below summarises the long-term stakeholder-driven assumptions considered in the analysis.

Table E.1: Long-term (non-energy) pathways and assumptions for the agriculture sector

Sl. No	Scenarios	Unit	2019 (Baseline)	2070 (Current Policy Scenario)	2070 (Net Zero Scenario)
1	Cropping intensity	% (Gross Cropped Area/Net Sown Area)	151	165	180
2	Crop diversification (away from rice, wheat, sugarcane)	% area shifting from rice, wheat, sugarcane	0.23	15	20
3	Sustainable Yield Intensification (SYI)	% reduction in yield gap	66% yield gap	20	70
4	Natural and Chemical-free farming	% Net Sown Area	<5%	20	25
5	Fertiliser Uptake Efficiency (FUE)	% nutrient uptake per kg fertiliser applied	33	40	50
6	Sustainable Rice Cultivation (SRC) practices	% of area under rice	0.25	20	25
7	Enhanced in-milk bovine productivity	kg/head/day	5.27	12	15
8	Share of in-milk population	% of total bovine population	30	45	55
9	Reduced crop residue burning	% reduction	0	30	60

Table E.2: Long-term energy transition pathways and assumptions for the agriculture sector

Sl. No	Levers	2020	2070 (Current Policy Scenario)	2070 (Net Zero Scenario)
1	Irrigated share of Gross Cropped Area	53%	65%	60%
2	Groundwater/ Pumping share	65%	65%	60%
3	Water Productivity Improvement	-	10%	25%
4	Share of Solar Pumps	2%	40%	60%
5	Share of Electric Pumps	70%	60%	40%
6	Pump efficiency (Solar & Electric)	36%	40%	50%
7	Pumping Head (metre)	28	50	35

Sl. No	Levers	2020	2070 (Current Policy Scenario)	2070 (Net Zero Scenario)
8	Mechanisation level	47%	100%	100%
9	Tractor:tiller split	95:5	70:30	50:50
10	Energy intensity per ha (MJ/ha) (% reduction in energy intensity)	Tractors:880 Tillers: 960	-20%	-40%
11	Fuel Consumption in Land Preparation	100% diesel	9% diesel, 8% CNG, 83% electric	99% Electric, 1% CNG/ Compressed Biogas (CBG)

Modelling Insights

Modelling for non-energy pathways and mitigation co-benefits

Strategic scaling of nine (9) pathways (Table E.1) could unlock up to ~26% of the sector's mitigation co-benefits in the Net Zero Scenario (NZS) against the Current Policy Scenario (CPS).

Under the Current Policy Scenario (CPS), agricultural emissions (non-energy) are expected to rise from ~506 $MtCO_2e$ in 2019 to ~531 $MtCO_2e$ in 2070 (Figure E.1). This is driven by a ~20% increase in livestock sub-sector and a ~21% decline in crop sub-sector (Figure E.2 and E.3). Contrarily, Net Zero Scenario (NZS) is expected to deliver total emissions of ~399 $MtCO_2e$ in 2070, with ~44% of decline in crop sub-sector and ~8% from livestock sub-sector (Figure E.2 and E.3). As a result, Net Zero Scenario could deliver ~25% mitigation co-benefits relative to the CPS (Figure E.1). Table E.3 highlights key drivers of such substantial mitigation co-benefits.

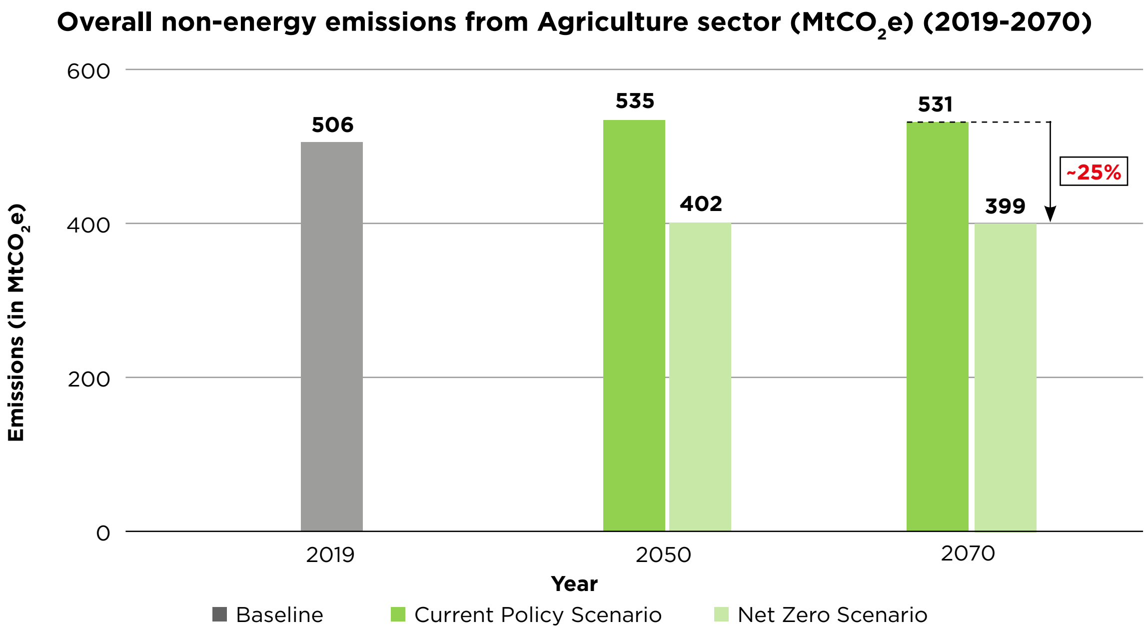

Figure E.1: Overall agriculture (non-energy) emissions in Current Policy Scenario and Net Zero Scenario (2019-2070)

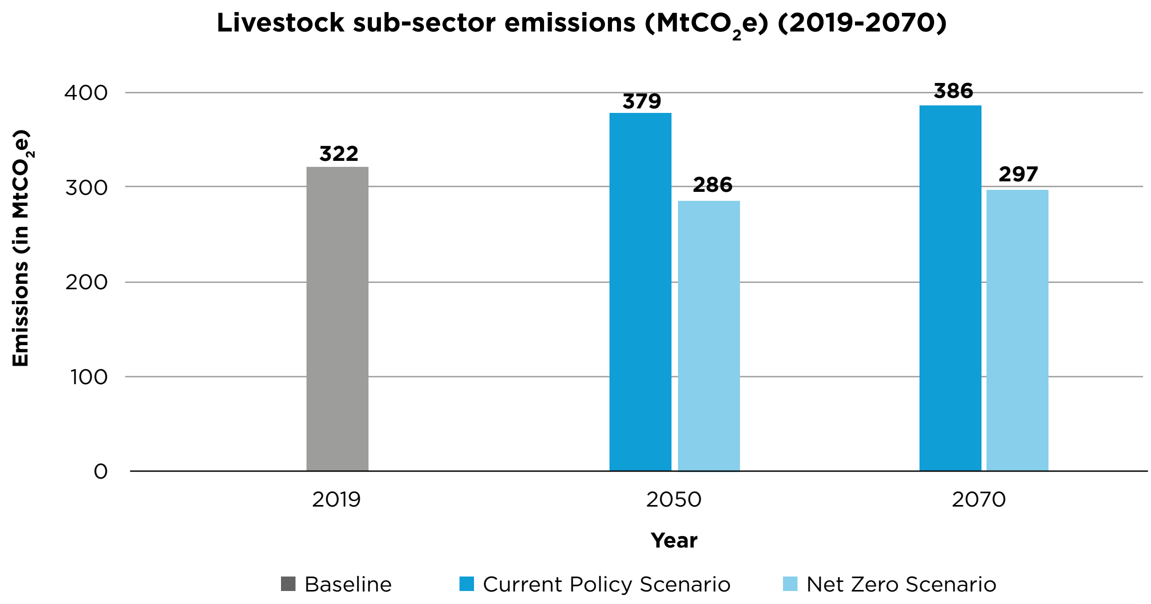

Figure E.2: Livestock sub-sector emissions in Current Policy Scenario and Net Zero Scenario (2019-2070)

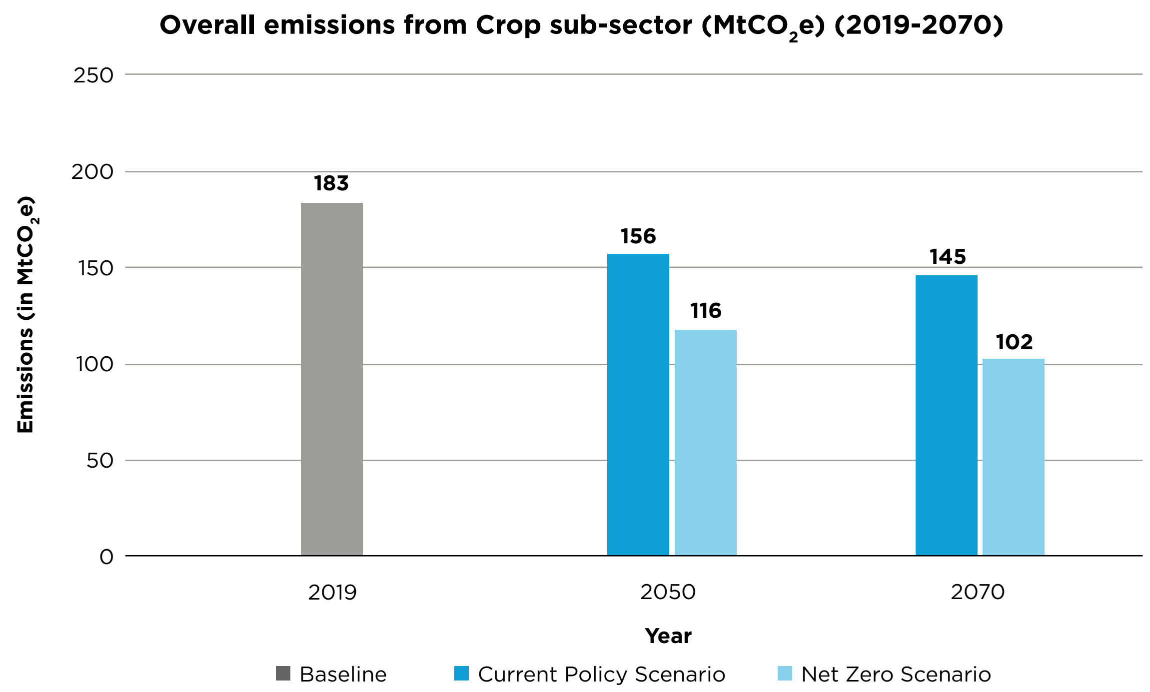

Figure E.3: Crop sub-sector emissions in Current Policy Scenario and Net Zero Scenario (2019-2070)

Table E.3: Key drivers for achieving 26% of mitigation co-benefits in 2070

Rice	Agriculture soils	Livestock
Three-pronged approach to counter resource-intensive rice cropping systems: 1. Crop diversification in areas away from rice, wheat, and sugarcane towards horticulture, pulses, nutri-cereals etc. 2. Sustainable Yield Intensification through technological (for example high yielding varieties etc.) interventions. 3. Adoption of sustainable rice cultivation practices that enhance water-use efficiency. For example: alternate wetting and drying (AWD), system of rice intensification (SRI), direct seeded rice (DSR), etc.	Two-pronged approach for soil health enhancement amidst the rising cropping intensity: 1. Improving Fertiliser Use Efficiency (FUE) through informed and optimised fertiliser use through *Soil Health Cards* (SHCs), adoption of neem-coated urea. 2. Adoption of Natural and Chemical-free farming via *National Mission on Natural Farming* (NMNF), *Paramparagat Krishi Vikas Yojana* (PKVY) etc.	Two-pronged approach for enhancing the overall efficiency of the livestock sector: 1. Enhancement of the productivity of in-milk bovine animals through animal nutrition interventions through dedicated programmes on fodder and also breed improvements. 2. Improving the share of in-milk bovines in the total livestock population through animal health-related programmes under the *National Livestock Mission* (NLM) (For example: Veterinary services).

Modelling Energy Transition Pathways

Scaling eleven (11) pathways (Table E.2) could deliver ~30% energy savings in Net Zero Scenario against Current Policy Scenario

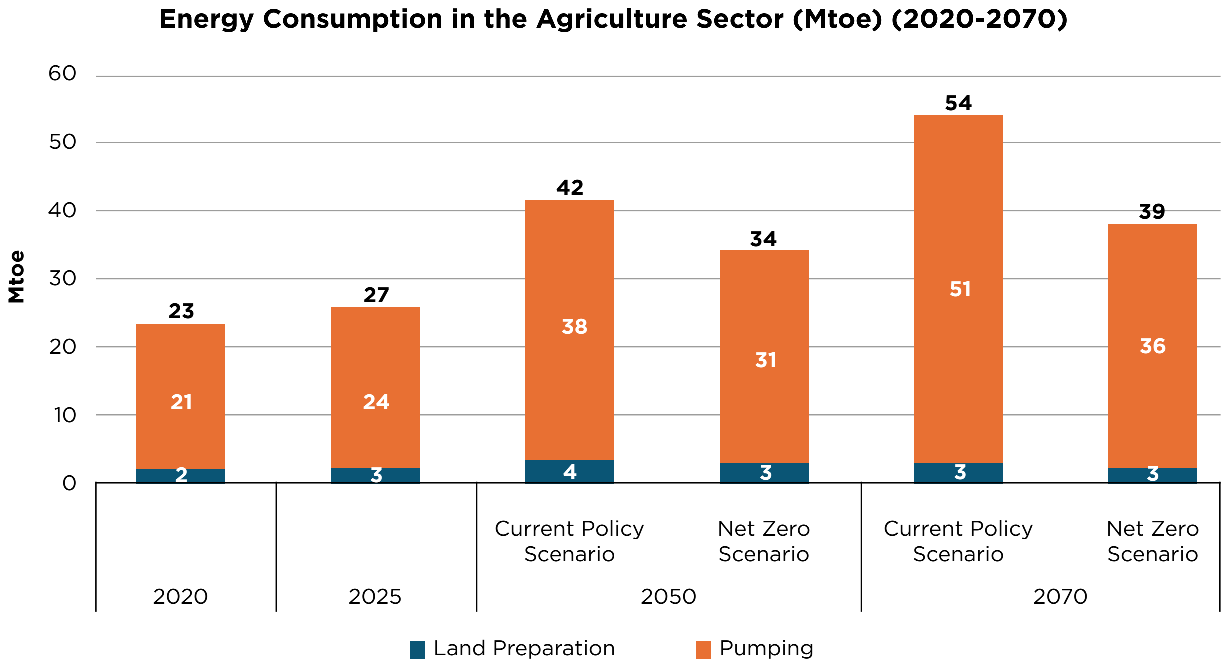

Figure E.4: Overall energy consumption (Mtoe) in Agriculture Sector (2020-2070)

In 2020, India's agriculture consumed ~23 Mtoe, dominated by irrigation pumping. By 2070, under the Current Policy Scenario, total demand rises to ~56 Mtoe, driven by expanding irrigation, high groundwater use, and mechanisation. Pumping dominates with ~52.5 Mtoe (mostly grid electricity, diesel, and 40% solar) followed by land preparation at ~3.7 Mtoe. Under Net Zero Scenario, energy stabilises at ~39 Mtoe, with pumping plateauing at ~36.8 Mtoe (60% solar, 40% grid) and land preparation at ~2.7 Mtoe, powered by electric tractors (~2.23 Mtoe) and Compressed Biogas (CBG) (~0.29 Mtoe) (Figure E.4). Efficiency gains, drip/sprinkler irrigation, aquifer recharge, and technology shifts decouple energy use from rising production, while Compressed Biogas (CBG) supported by *Sustainable Alternative Towards Affordable Transportation* (SATAT) scheme, reduces residue burning, and generates rural income.

Key Suggestions

1. **Develop intervention specific, targeted roadmaps:** To maximise mitigation and energy-efficiency co-benefits, policymakers must adopt a risk-calibrated, evidence-based approach that integrates both supply and demand-side levers. Supply-side, adaptation-centric pathways alone deliver ~25% of total mitigation co-benefits by 2070 (Figures E.1 & E.4), underscoring the necessity of complementary demand-side shifts. On the demand side, this includes rationalising energy use in agriculture and enabling dietary transitions towards less resource-intensive, nutritionally dense foods. For instance, shifting consumption from water and energy intensive rice towards climate-resilient millets can reduce emissions while strengthening resilience. This could be supported by behaviour-change initiatives such as the *Eat Right Movement* and *National Millet Mission* (NMM). To ensure that such transitions scale without compromising farmer incomes or food and nutritional security, the government must deploy phased, spatially targeted, and socio-economically differentiated roadmaps, particularly for scaling natural and chemical-free farming interventions.

2. **Institutionalize an integrated "agri-food" systems framework:** No single intervention can independently deliver meaningful mitigation or energy-efficiency co-benefits. Achieving these outcomes requires an integrated approach that coordinates production systems, dietary patterns, value chains, and environmental objectives across land, energy, food, health, biodiversity and water systems. *The Pradhan Mantri Dhan-Dhaanya Krishi Yojana* (PMDDKY) exemplifies the potential of such integration by converging multiple objectives and programmes, including crop diversification, rural livelihoods, and access to credit, across 100 low-productivity districts. Scaling similar initiatives using a whole-of-government approach, with alignment across the Ministries of Agriculture, Energy, Water, and Health, can embed clean energy, healthy diets and other low-emissions interventions directly into agricultural development strategies. Such coordination enables coherent policy design, reducing trade-offs and preventing fragmented interventions that risk generating competing or counterproductive outcomes.

3. **Conduct Integrated Assessment Modelling (IAM) to guide ambition setting and long-term planning:** Forward looking planning to achieve mitigation co-benefits by 2070 requires evidence generation to evaluate trade-offs and synergies across farmer livelihoods, food and nutritional security, and long-term resilience. Integrated Assessment Models (IAMs) provide a data-driven framework to systematically link socio-economic trajectories, climate risks, and policy levers such as carbon pricing and subsidy reform. When deployed effectively, integrated assessment frameworks can inform policy design and implementation across

national, state, and local levels of government, enabling the evaluation of both direct impacts and second-order outcomes across land, energy, food, water and other systems.

4. **Implement an "Efficiency-first + clean energy solutions" strategy to achieve maximum efficiency within the sector:** The energy demand, dominated by irrigation, must be managed through an adaptation-first, agriculture-led approach, with energy interventions sequenced subsequently to avoid energy-intensive lock-ins. An efficiency-first strategy should prioritise resource-efficient practices such as micro-irrigation, sustainable crop management, and rationalised input subsidies to strengthen resilience and reduce input intensity. Building on these adaptation gains, energy interventions, including renewable adoption, electrification, and Compressed Biogas (CBG), can then be deployed to decouple productivity growth from energy use. Leveraging Custom Hiring Centres (CHCs) to expand access to clean mechanisation for smallholders ensures that productivity gains translate into mitigation and energy efficiency co-benefits without embedding high energy requirements.

Background

As India advances towards its Viksit Bharat vision by 2047 (PMO, 2023) and Net Zero emissions by 2070 (MoEFCC, 2022), agriculture occupies a critical position at the intersection of economic transformation, food security, and climate change. The sector supports nearly 46% of the population, and is dominated by small and marginal landholders. Despite facing multiple shocks, including the COVID-19 pandemic and global geopolitical disruptions, Indian agriculture has demonstrated resilience. Between 2017–18 and 2024–25, the sector sustained an average annual growth rate of 5.22%, reinforcing its importance as a stabilising force within the broader economy (MoF, 2025). However, this performance masks deep structural challenges that threaten long-term sustainability and climate resilience.

Indian agriculture operates under rising climate risks, with small and marginal holders bearing a disproportionate share of the burden. These pressures jeopardise farm livelihoods, weaken production systems, and push households into deeper vulnerability. The challenge is further intensified by widespread resource degradation, notably declining soil health and escalating water stress.

However, agriculture sector also have substantial environmental footprint. It contributes about ~14% of India's total greenhouse gas (GHG) emissions (MoEFCC, 2024), primarily from non-CO_2 gases and remains energy-intensive, accounting for 18–20% of national electricity consumption and ranking second in diesel use (CEA, 2024).

Looking ahead, the sector's vulnerability is likely to intensify due to rising heat stress, increasing rainfall variability, and growing pressure on land and water resources, compounded by structural constraints such as small and fragmented landholdings, high dependence on climate-sensitive livelihoods, and limited adaptive capacity among smallholders. For instance, groundwater-dependent irrigation systems heighten exposure to droughts and energy price shocks.

The sector faces high climate vulnerability and deep structural constraints, given its role in livelihoods and food security. By 2070, the sector must feed billions, respond to evolving dietary preferences and meet rising bioeconomy demands for feed, fibre, and bioenergy.

Consequently, agriculture in India cannot be approached through a narrow mitigation-centric lens. For India, the priority is safeguarding productivity, farmers' income and food and nutritional security. This shall require focus on measures to build resilience to climate change. A mitigation-focused approach risks exacerbating rural distress and undermining development outcomes. Therefore, this **report has taken a "differentiated" approach than what is adopted in other sectoral reports in this series. It focuses on adaptation-first pathways**[1] **that support livelihoods and food and nutritional security, and assesses their corresponding abilities in generating**

1 Find strategies with their adaptation and mitigation outcomes in Table 2.3

mitigation co-benefits. For instance, diversification away from water-intensive cereals towards pulses, oilseeds, and millets strengthens drought resilience and income stability, while mitigation benefits arise through lower input use, reduced energy demand, and improved soil carbon, leading to lower emissions intensity.

India has already initiated such multi-benefit approaches through programmes including the *National Mission on Sustainable Agriculture* (NMSA), *Crop Diversification Programme* (CDP), *National Mission on Natural Farming* (NMNF), *National Millet Mission* (NMM) among others. These initiatives demonstrate how resilience enhancement, and resource conservation can also contribute to lower emission intensity (MoF, 2025;MoEFCC, 2024).

Recognising this imperative, NITI Aayog has constituted a multi-ministerial Working Group on the Agriculture Sector. This 42-member inter-disciplinary group operates with the objective:

To develop and analyse various options/pathways to achieve long-term resilience, farmers' incomes, and food and nutritional security that deliver mitigation co-benefits, considering the impacts of technology, policy, investment, ecology-based farming systems, and others.

The Terms of Reference (ToR) of the Working Group are:

1. To provide a comprehensive understanding of future trends in agricultural production of major food commodities, including milk, through 2050 and 2070
2. To project non-energy emissions and energy demand through 2070 in India's current policy framework
3. To identify and develop long-term pathways that ensure farmers' income, ensure resilience and food and nutritional security that could deliver mitigation co-benefits.
4. To estimate overall mitigation co-benefits associated with the proposed pathways and evaluate their effectiveness in supporting India's climate goals.

Box 1: Scope of the Working Group

The Agriculture, Forestry, and Land Use (AFOLU) sector in India has exhibited a net-negative emissions trend since 2018, primarily due to land-use-related carbon sequestration offsetting agricultural emissions (MoEFCC, 2024). However, the focus of this study is on understanding gross emissions from the agriculture sector (not accounting sequestration). The study aims to provide a detailed assessment of various adaptation-centric interventions with mitigation co-benefits in the agriculture sector from non-energy use.

1

INTRODUCTION

Introduction

1

1.1. HISTORICAL TRENDS IN AGRICULTURAL PRODUCTION AND GROWTH

India's agricultural growth trajectory over the past five decades has been shaped by sustained gains in productivity. In the pursuit of food security, the country more than doubled its food grain production between 1970 and 2010, rising from ~108 to ~244 million tonnes (Agriculture Statistics, 2023). Over the same period, milk production increased nearly fivefold, from ~22 to ~122 million tonnes, positioning India as the world's largest producer. These achievements were driven by transformative interventions under the Green Revolution and the White Revolution, which expanded access to improved seed varieties, irrigation, fertilisers, veterinary services and institutional support (John and Babu, 2021).

The momentum in agricultural output has continued in the last decade, reflecting improvements in agricultural productivity and policy support. Between 2011 and 2019, food grain production increased to ~285 million tonnes and further to ~332 million tonnes in 2023-24 (PIB,2011; PIB,2019; Agriculture Statistics, 2023), while milk production rose sharply to ~198 million tonnes (DAHD, 2023). Such production gains were largely achieved through productivity improvements over area or herd size expansion.

For example, rice yields increased by ~14% between 2011 and 2019, from ~2.3 to ~2.7 tonnes per hectare, while the area under rice cultivation remained broadly stable at around 44 million hectares (Agriculture Statistics, 2023) (Figure 1.1 & 1.2). As a result, rice production increased from ~105 in 2011 to ~119 million tonnes in 2019 (Figure 1.3). This reflects the widespread adoption of high-yielding varieties supported by expanded irrigation coverage under the *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY).

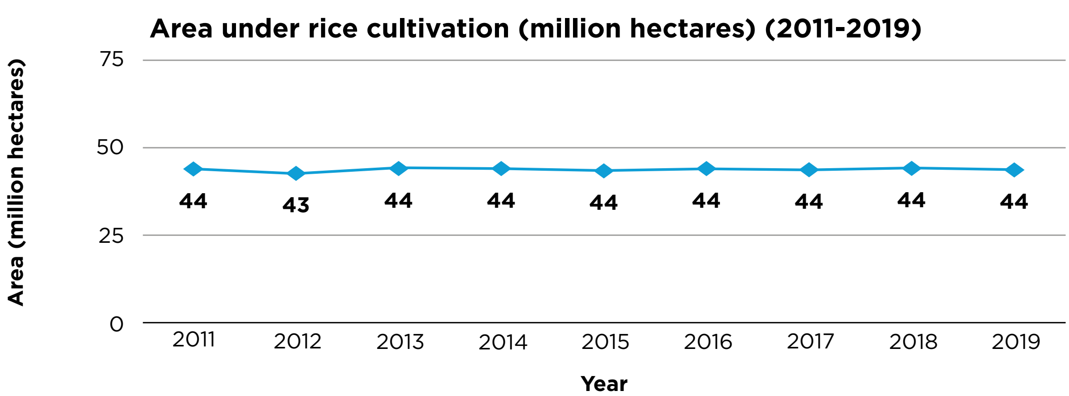

Figure 1.1: Historical trends in rice acreage (2011-2019)

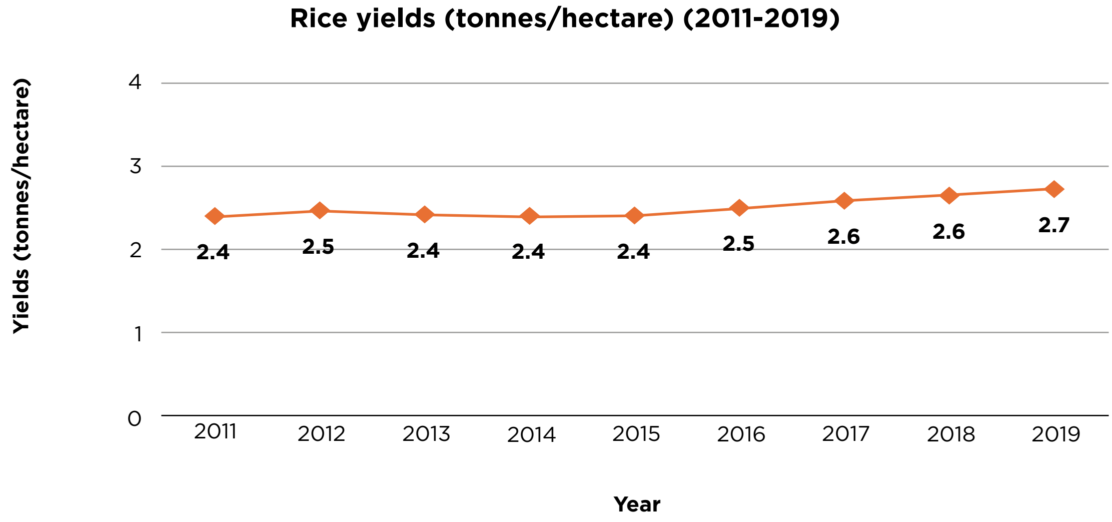

Figure 1.2: Historical trends in rice yields (2011-2019)

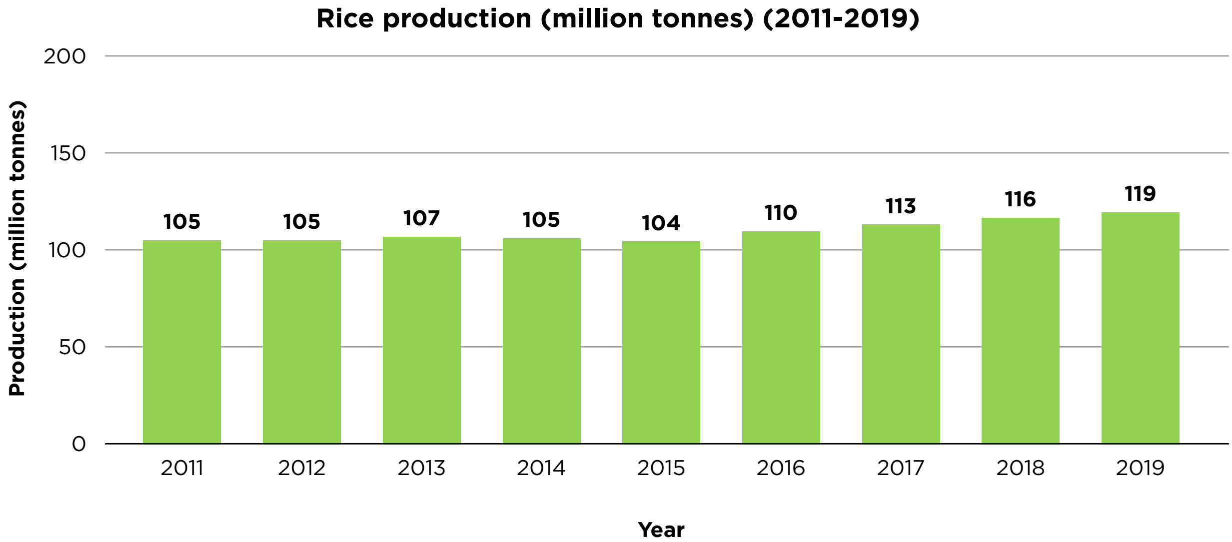

Figure 1.3: Historical trends in rice production (2011-2019)

Similarly, the livestock sector witnessed strong productivity gains. Average milk yield per in-milk bovine increased by ~28.5%, from 4.10 kg/day in 2011 to 5.27 kg/day in 2019 (DAHD 2023), supported by policy initiatives such as the *National Dairy Plan* and the *National Livestock Mission* (Figure 1.4). Structural changes in herd composition further reinforced these gains. Between 2012 and 2019, the share of female bovines increased from 72% to 81% (DAHD 2019), alongside a gradual shift from low-yielding to higher-yielding and crossbred animals (Figure 1.5). These trends enabled rapid growth in milk output while maintaining relative stability in the overall bovine population.

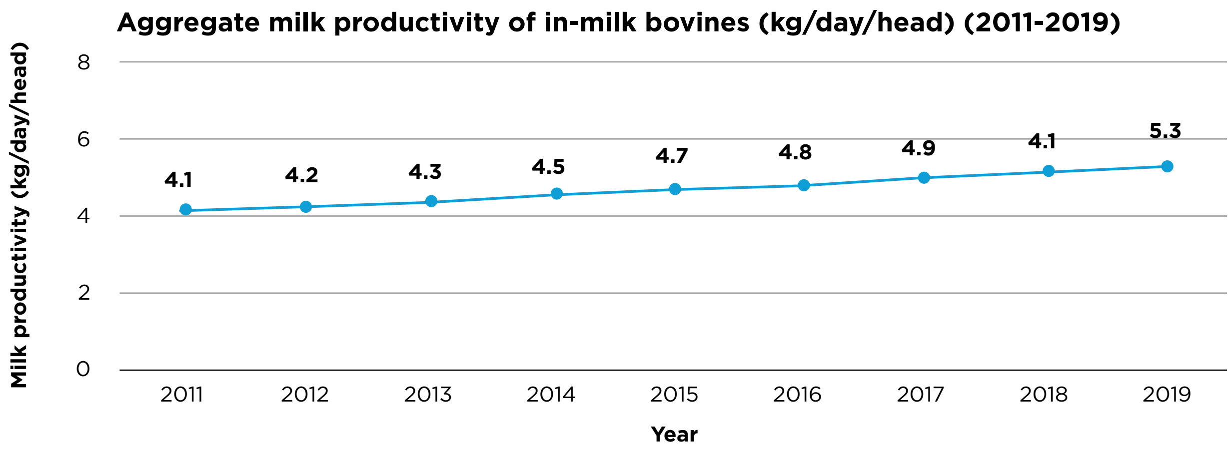

Figure 1.4: Historical trend of milk productivity (2011-2019) (DAHD, 2018, 2019)

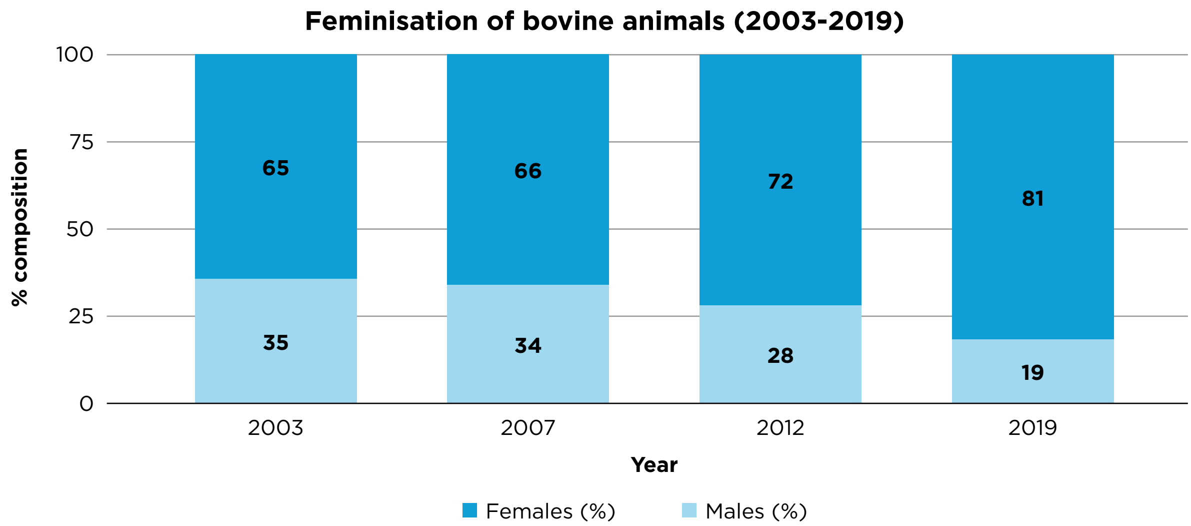

Figure 1.5: Trends in share of female bovines in total herd composition (2003 – 2019) (DAHD, 2019)

Taken together, these historical trends highlight a defining feature of Indian agriculture: output growth driven predominantly by productivity improvements, supported by public investment, technology adoption and institutional reforms. This foundation is critical for understanding how the sector now intersects with emerging climate-related challenges.

1.2. CLIMATE CHANGE, AGRICULTURE VULNERABILITY AND EMISSIONS PROFILE

Agriculture in India is acutely exposed to climate risks. Frequent dry spells (Chuphal et.al, 2024) and extreme rainfall events (Prabhu and Chitale, 2024) have been disrupting yields. Rising temperatures and shifting precipitation patterns are projected to reduce crop productivities by

8–12% by 2099 (MoF, 2025). These climate impacts are compounded by resource degradation: declining soil organic carbon, unsustainable fertiliser use, and water stress linked to input-intensive cropping systems (Birthal et al, 2014; MoEFCC, 2022). Together, these pressures are jeopardising farmer livelihoods and weakening resilience by elevating costs and risks.

At the same time, the agriculture and allied sectors currently contribute ~13.7% to India's Greenhouse Gas (GHG) emissions (MoEFCC, 2024), predominantly from non-CO_2 GHGs such as methane (CH_4) and nitrous oxide (N_2O). These gases have global warming potentials (GWP) of 28 and 265 times that of CO_2 over 100 years (IPCC, 2014). Currently, it is responsible for ~75% of India's CH_4 and ~73% of its N_2O emissions, driven by enteric fermentation from livestock, rice cultivation, and synthetic fertiliser use (Table 1.1) (Patange et al, 2024; MoEFCC, 2021).

In 2019, livestock emissions dominated agricultural emissions at ~60%, through enteric fermentation (~53%) and manure management (~7%). This is followed by emissions from agricultural soils (~21%) and methane from rice cultivation (~17%). Historical data indicates that agricultural non-energy emissions increased marginally by ~3% from ~409 $MtCO_2e$ in 2011 to ~421 $MtCO_2e$ in 2019 (Figure 1.6) (MoEFCC, 2021). This is despite a ~19% growth in food grain production and a ~55% growth in milk production, over the same period (Agriculture Statistics, 2023; DAHD 2023). This stabilisation of emissions in the last decade against significant production gains is primarily due to:

a. Rice yield improvements by ~14% from 2.39 to 2.72 tonnes per hectare on a relatively constant rice acreage of 44 million hectare (Agriculture Statistics, 2023).

b. Relatively stable livestock population as a result of 22% rise in productivity, due to the following factors of herd restructuring:

   i. Transition from low-yielding to high-yielding animals (NITI Aayog, 2024);

   ii. Replacement of male bovines with female bovines, increasing the share of female animals in the overall population

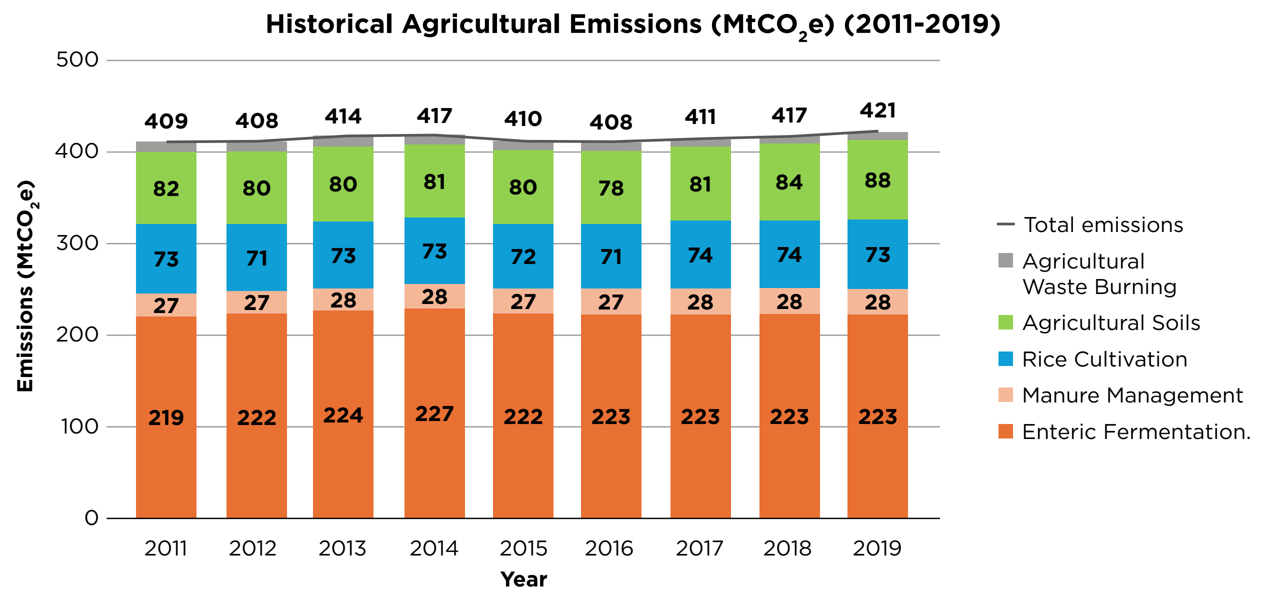

Figure 1.6: India's historical trends of agriculture non-energy emissions (AR2) (2011-2019) (MoEFCC, 2021)

In addition, the sector is a major energy consumer, accounting for ~18% of national electricity consumption and ranking second in diesel use (CEA, 2025). The emissions from diesel and other fossil-fuel consumption in land-preparation and pumping are accounted as agriculture energy emissions. In this study, the emissions from the electricity use in the agriculture sector are accounted for in power sector emissions. Table 1.1 summarises the detailed description of agriculture sector's energy and non-energy emission sources.

As shown in Figure 1.6, in 2019, livestock emissions dominated agricultural emissions at ~60%, through enteric fermentation (~53%) and manure management (~7%). This is followed by emissions from agricultural soils (~21%) and methane from rice cultivation (~17%) (MoEFCC 2021).

Understanding the major drivers of agricultural emissions is critical for interpreting historical trends, projecting future emission trajectories, and evaluating the effectiveness of policy interventions. The following section examines historical drivers in detail.

Table 1.1: Description of agricultural emissions categories and their sources

Source	Description of emission sources
Rice cultivation	Methane (CH_4) is produced in flooded rice fields through anaerobic decomposition of organic matter.
Agricultural soils	Nitrous Oxide (N_2O) is emitted from soils due to nitrogen inputs such as fertilisers and manure, through microbial processes including nitrification and denitrification.
Agricultural waste burning	Both CH_4 and N_2O are released during burning of crop residues, primarily due to incomplete combustion of biomass and nitrogen-containing plant material.
Enteric fermentation	CH_4 is generated in the digestive system of ruminant livestock as microbes break down feed, and is mostly expelled via belching.
Manure management	CH4 and N_2O are emitted during storage and treatment of manure, where anaerobic conditions produce methane, and microbial processes release nitrous oxide from nitrogen compounds.
Land preparation and Pumping	Emissions (CO_2e) due to fossil fuel consumption for land preparation and pumping.

1.3. HISTORICAL TRENDS IN NON-ENERGY EMISSIONS FROM AGRICULTURE SECTOR

Methane Emissions from Rice Cultivation

Methane (CH_4) emissions from rice cultivation is due to methanogenesis, driven by anaerobic soil conditions and flooded water regimes. As a result, overall rice emissions in India are driven by two factors: the spatial extent (acreage) of rice cultivation and the rice water-management regimes (MoEFCC, 2022). While rice production increased between 2011 and 2019, emissions from rice cultivation remained broadly stable (Figure 1.7). This stabilisation reflects consistent water management practices with potential shifts in space. While conventional flooded systems persist in states such as Punjab, Haryana, West Bengal and Rajasthan, water-scarce states such as Tamil Nadu and Karnataka have increasingly adopted Alternate Wetting and Drying (AWD) and aerobic rice systems. These sustainable rice cultivation practices reduce methane emissions by ~48% (Annexure III) per hectare (emission intensity) offsetting emission pressures from productivity-led intensification.

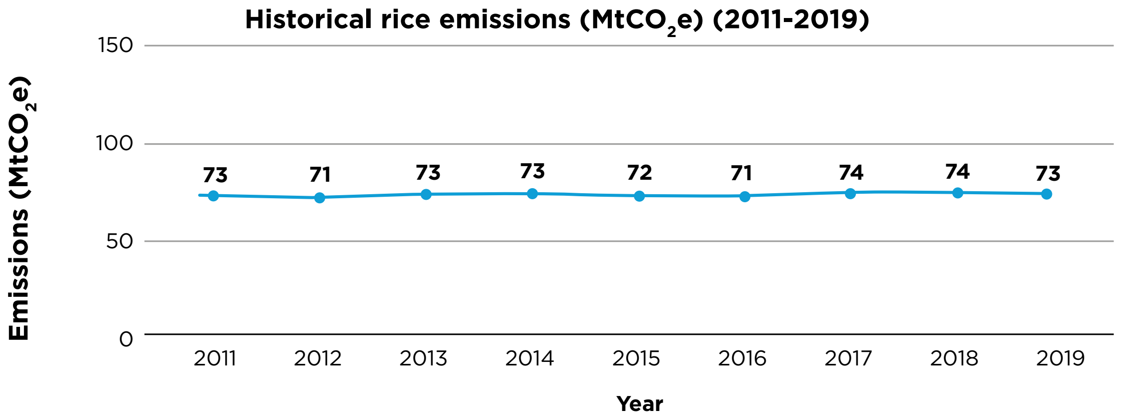

Figure 1.7: Historical trends of emissions from rice cultivation (AR2) (2011-2019) (MoEFCC, 2022)

Nitrous Oxide (N2O) Emission from Agricultural Soils

N_2O emissions from agricultural soils in India are primarily driven by two factors: nitrogen application rates[2] per cropping cycle (kg/ha) – including both synthetic fertilisers and organic inputs – and cropping intensity (number of cropping cycles per year – GCA/NSA), which determines how frequently nitrogen is applied per hectare in a year (IPCC, 2014).

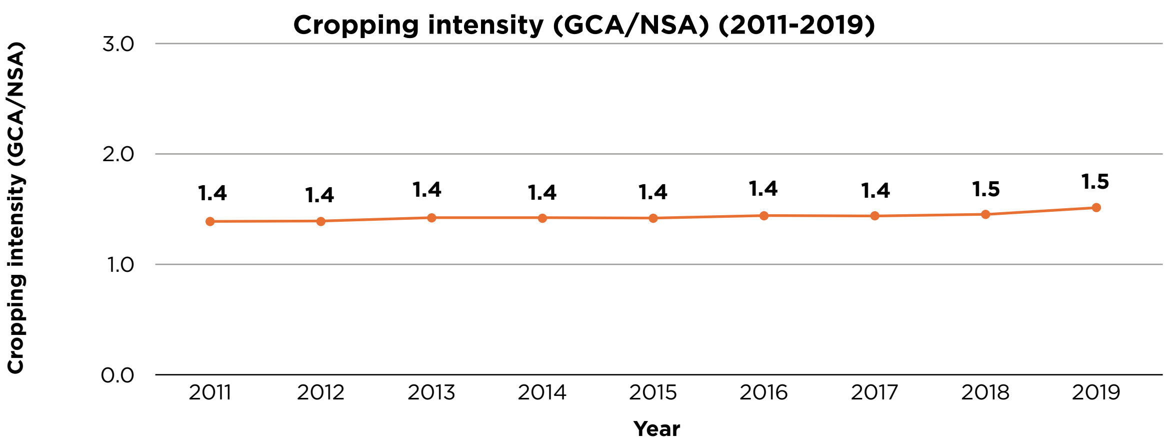

Figure 1.8: Trends of cropping intensity (2011-2019)

2 Rate of application of nitrogen refers to the amount of nitrogen inputs applied per ha (kg/ha).

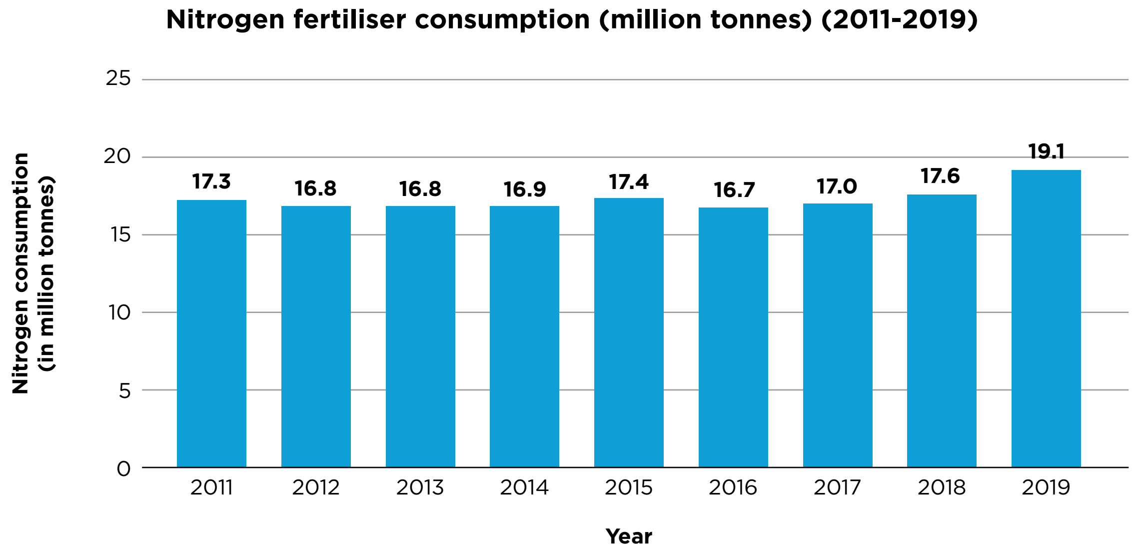

Figure 1.9: Total nitrogen fertiliser consumption (2011-2019)

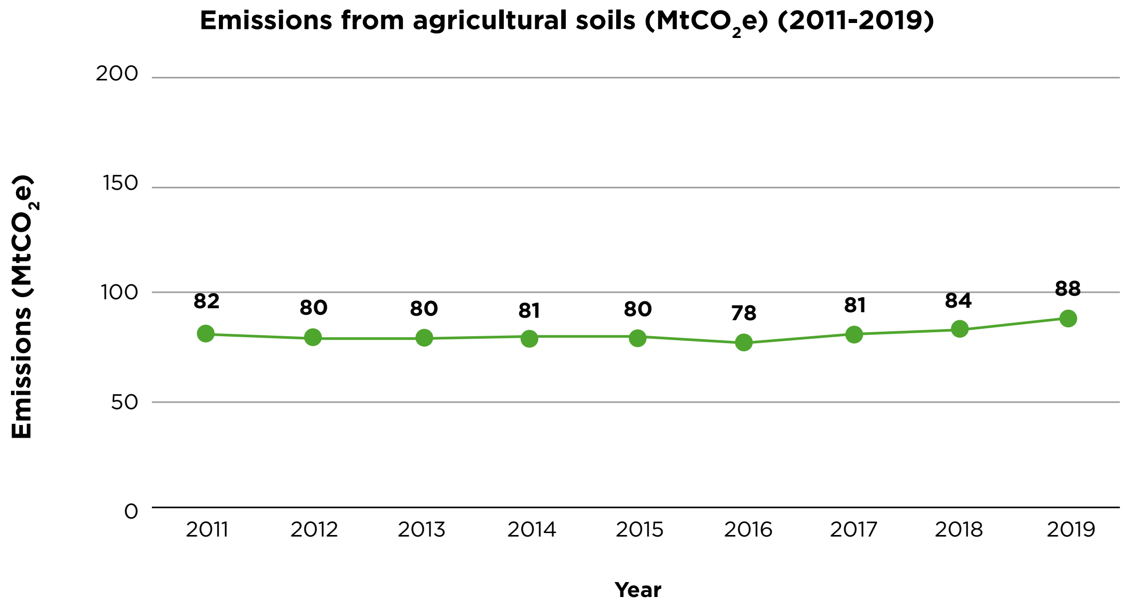

Figure 1.10: Emissions from agricultural soils (AR2) (2011-2019)

India is one of the world's largest consumers of synthetic fertilisers with an average application rate of ~140 kg of total nutrients (N + P_2O_5 + K_2O) per hectare per cropping cycle (FAI, 2024). However, nutrient application is heavily skewed toward nitrogen, with an N:P:K ratio of 10.9:4.4:1 indicating significant overuse of nitrogen relative to others (FAI, 2024). As a result, agricultural soils emissions in India rose by ~7% from 82 to 88 $MtCO_2e$ between 2011 and 2019 (Figure 1.10). This was in parallel to a 10.4% increase in overall fertiliser consumption from ~17 to 19 million tonnes (FAI, 2024) (Figure 1.9).

The rise in fertiliser consumption can be attributed to two main factors. First, cropping intensity increased from ~139% to ~151% between 2011 and 2019 Figure 1.8), driven by expanded irrigation under *Pradhan Mantri Krishi Sinchai Yojna* (PMKSY). Second, declining *Nitrogen Use Efficiency* (NUE) (Singh, 2023) led to higher per-hectare nitrogen application, which rose from ~88.5 to ~90.4 kg/ha over the same period (FAI, 2024). Nitrogen use from organic sources also grew by ~1.44%, further increasing soil emissions. While programs like the Paramparagat Krishi Vikas Yojana (PKVY) and the *National Mission on Natural Farming* (NMNF) promote organic alternatives that reduce emissions, their adoption remains limited (<3% of cropland) (NITI Aayog, 2024), suggesting that these emission trends may persist.

Livestock Emissions: Enteric fermentation (CH_4) and Manure Management (N_2O + CH_4)

The emissions in the livestock sector are driven by methane from enteric fermentation and by methane and nitrous oxide from manure management. Bovine animals, cattle and buffaloes, are the dominant source of livestock emissions, accounting for ~82%[3] of livestock emissions in 2019. Given this dominance of bovine animal emissions in the livestock sub-sector, this analysis focuses specifically on bovine-related emissions.

Milk production rose by ~55% between 2011 and 2019, growing from ~128 million tonnes to ~198 million tonnes (Figure 1.11). However, emissions from the livestock sector showed a moderate growth of only 2.23%, from ~246 MtCO_2e to ~251 MtCO_2e (Figure 1.12).

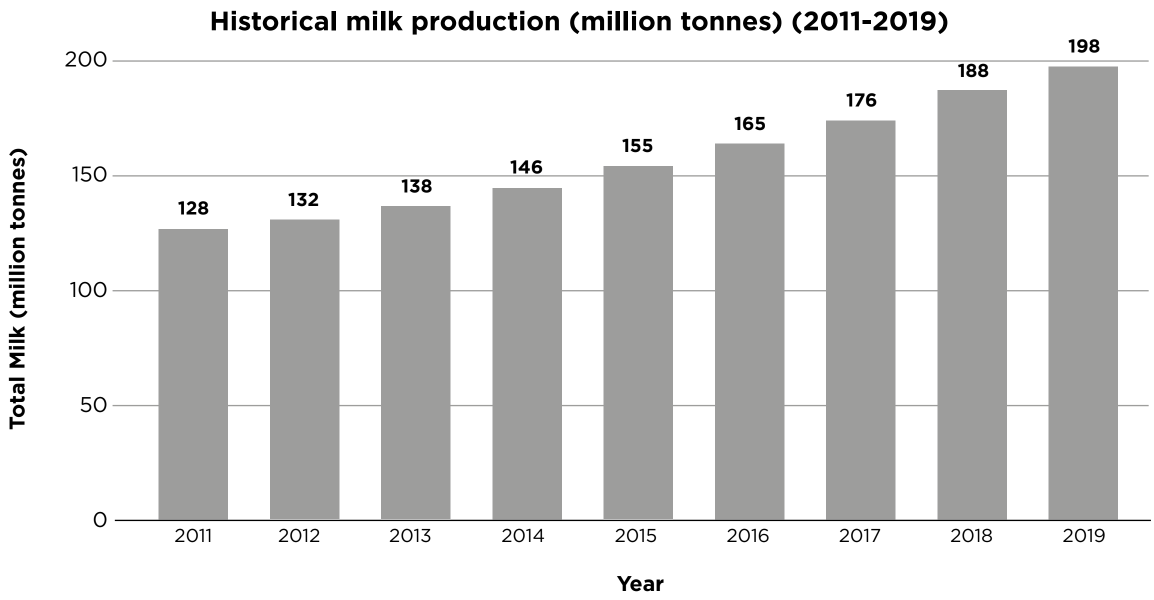

Figure 1.11: Historical milk production (DAHD, 2018, 2019, 2023)

3 (Authors' analysis based on MoEFCC 2021)

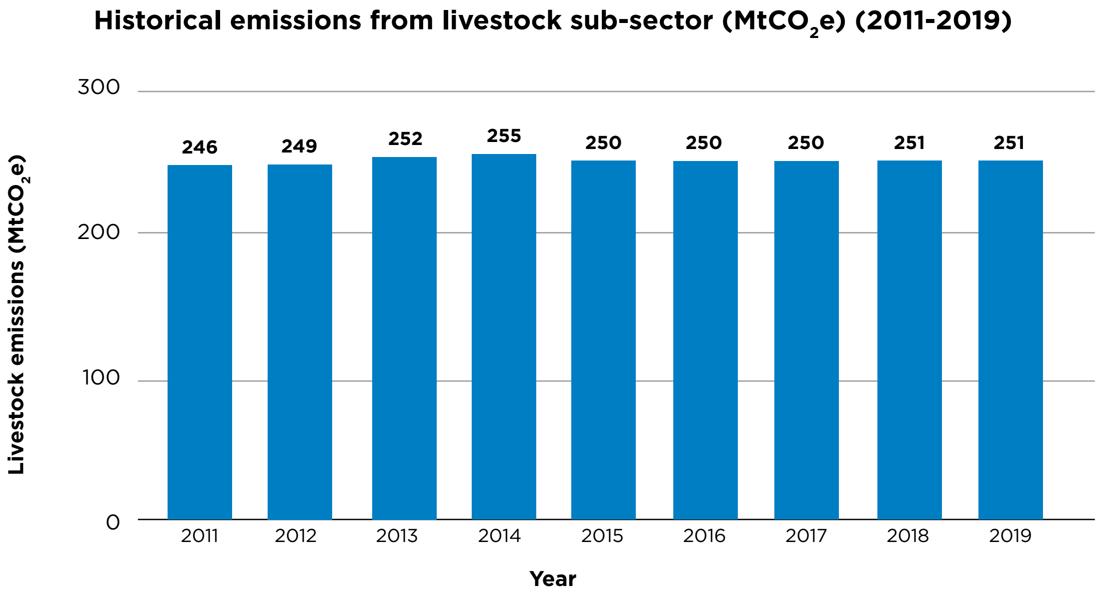

Figure 1.12: Historical livestock emissions (AR2) (2011-2019) (MoEFCC, 2021)

Such stabilisation trends in livestock emissions are primarily driven by (i) an increase in bovine productivity (Figure 1.4) and (ii) the displacement of male animals by and with the increasing female population, keeping the total bovine population stable so far (Figure 1.5).

2

METHODOLOGY

Methodology

2

2.1 APPROACH TO ESTIMATING MITIGATION CO-BENEFITS OF NON-ENERGY AGRICULTURAL PATHWAYS

As mentioned in the Background, this report has taken a "differentiated" approach than what is adopted in other sectoral reports in this series. It focuses on adaptation-first pathways that support livelihoods and food and nutritional security, and assesses their corresponding abilities in generating mitigation co-benefits. However, this requires integrated frameworks that address synergies and trade-offs across different time scales (IPCC 2019). This analysis is limited to supply-side, production-oriented, scenario-based modelling of agricultural emissions.

This section details the report's approach followed to:

1. **Production projections:** Compile historical and baseline (2019) production data for crops and livestock, and project production trajectories for eight major crops and milk through 2070.
2. **Emissions assessment:** Estimate sectoral greenhouse gas emissions from crops and livestock through 2070, based on projected production pathways.
3. **Policy pathway analysis:** Develop two long-term policy pathways—the Current Policy Scenario and the Net Zero Scenario—aligned with resilience, farmer incomes, and food and nutritional security, and assess and quantify associated mitigation co-benefits

Figure 2.1 shows the methodology for estimating future emissions from non-energy use. It uses 2019 as the baseline year and employs an annual time-step model[4] to project emissions trajectories from 2020 to 2070, with intermediary milestones of 2047[5].

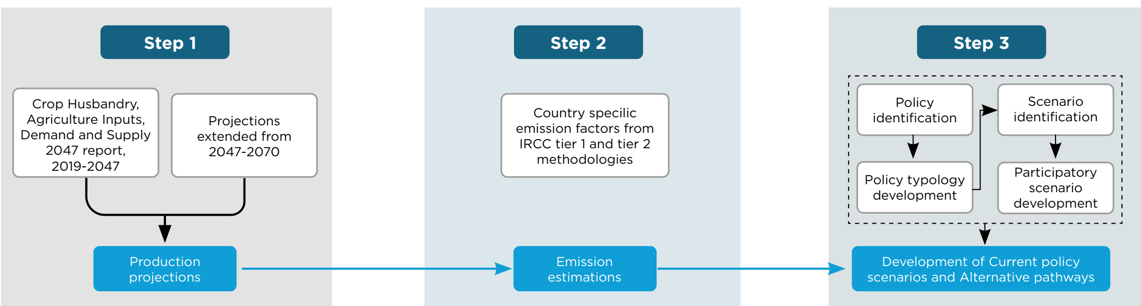

Figure 2.1: Agriculture emission modelling methodology

4 An annual time-step model projects year-by-year changes by updating key variables and recalculating emissions each year.

5 India's timeline to become a developed nation,Viksit Bharat, on the occasion of centenary year of Independence

Step 1: Compiling historical and baseline (2019) production data for crops and livestock and projecting future production for 8 major crops and milk.

Consistent with the supply-side scope of this analysis, agricultural emissions are modelled using production projections of nine key food commodities - for 8 major crops[6] and milk.

a. For the period 2021–2047, production projections are directly adopted from NITI Aayog's *"Crop Husbandry, Agriculture Inputs, Demand and Supply"* (2024), which applies a time-series methodology grounded in historical area, production and yield trajectories (see Box 2).

b. For the period 2048–2070, production projections are extended from the 2047 endpoints using the methodology adopted in the NITI Aayog (2024) report, ensuring continuity and methodological consistency through 2070.

Box 2: Methodology followed for Forecasting the Production of Food Commodities

The Working Group Report on Crop Husbandry, *Agriculture Inputs, Demand and Supply*, Report of 2024 of NITI Aayog assess trends in demand and supply of food commodities, inputs, and feasible levels of exports through 2047. The report uses four forecasting methods for projecting supply/production based on historical trends of change. They are: a) Autoregressive Integrated Moving Average (ARIMA), b) Artificial Neural Network (ANN), c) Holt's smoothing, and d) the exponential growth rate model (based on the past 10 years).

Step 2: Emission estimations through 2070

Emissions are estimated using the IPCC Tier 1[7] and Tier 2[8] methodologies (Table 2.1). These estimates incorporate country-specific emission factors across five emission categories within the agricultural sector (Table 2.2). Methane (CH_4) and nitrous oxide (N_2O) are the dominant greenhouse gases in this sector; their emissions are therefore expressed in carbon dioxide equivalents (CO_2e) using 100-year Global Warming Potential (GWP) values of 28 for CH_4 and 265 for N_2O, as reported in the IPCC's Fifth Assessment Report (AR5). The baseline year for emissions projections is 2019, consistent with emissions reported in India's Third National Communication. To ensure methodological consistency across the analysis, historical 2019 emissions were converted from AR2 to AR5 GWP values.

6 Major eight crops are considered as they contribute directly to GHG emissions from the sector. These are: Rice, Wheat, Cotton, Jute, Rapeseed and Mustard, Maize, Sugarcane and Nutri-cereals

7 Tier 1 methodology uses IPCC default emission factors and general activity data; suitable for countries with limited data

8 Tier 2 methodology uses country-specific emission factors and detailed activity data. It requires better-quality national information and captures local conditions more effectively (India mostly uses Tier 2)

Table 2.1: Emission estimation methodology for various categories considered for the agriculture sector (MoEFCC, 2021)

Sector/Category	Gas	Method Used	Emission Factor
Enteric Fermentation	CH_4	T1, T2	D, CS
Manure Management	CH_4	T1	D
	N_2O	T1	D
Rice Cultivation	CH_4	T2	CS
Agricultural Soils	N_2O	T2	CS
Field Burning of Agricultural Residues	CH_4	T1	D
	N_2O	T1	D

Notation/Legend: T1: Tier 1; T2–Tier 2; CS–Country specific emission factors; D–IPCC Default emission factors

Table 2.2: Emission estimation methodology for various categories considered for the agriculture sector

Emission Category	GHG Emission Type	Emission Estimation Methodology
Livestock emissions	Enteric fermentation (CH_4) Manure Management (N_2O, CH_4)	To estimate livestock emissions from 2020 to 2070, bovine populations were projected (82% of total livestock emissions in 2019) using milk production projections. In-milk and non-in-milk animal numbers were derived from productivity trends and historical trends of herd composition. Emissions were computed by applying country-specific emission factors to these population categories (species type and dairy and non-dairy cattle based on their ages) as indicated in Annexure I. Given the limited contributions of the non-bovine animals, these emissions are assumed to remain constant at 2019 levels through 2070.
Rice emissions	Methane emissions (CH_4)	Between 2011 and 2019, rice cultivation in India maintained a stable emission intensity of 2.11 $MtCO_2e$/ha over 44 million hectares, reflecting consistent aggregate water management practices (Annexure I). Future emissions are projected by applying this emissions intensity to anticipated rice cultivation areas, assuming aggregate water regimes remain unchanged unless specified.
Agricultural soil emissions	Nitrous oxide emission (N_2O) based on soil activity	Agricultural soil (N_2O) emissions, categorised as direct and indirect, are estimated based on projections of total nitrogen consumption from both synthetic and organic fertilisers. Appropriate emission factors are applied to estimate emissions from agriculture soils are estimated by summing direct and indirect emissions (Annexure I)
Agricultural Waste Biomass (AWB)	Emissions from crop residue burning (N_2O, CH_4)	Crop residue burning represents a source of CH_4 and N_2O emissions and which is estimated based on the amount of crop residue burnt. Crop residue burnt is estimated using residue crop ratios, dry matter content, and combustion efficiency[9] for each of the eight major crops. CH_4 and N_2O emission factors were applied to the estimated biomass burnt to compute agricultural waste burning (AWB) emissions from 2020 to 2070 (Annexure I).

Note: The Annexure I provides detailed country-specific emission factors used across the five categories of emissions.

9 Median state-level combustion efficiency was used for rice, while national average values were applied for other crops

Step 3: Development of Current Policy Scenario (CPS) and Net Zero Scenario (NZS)

Two policy pathways: the Current Policy Scenario and the Net Zero Scenario—were developed to generate long-term emissions projections for India's agriculture and allied sectors. These pathways are structured around four food system based policy typologies and nine key interventions as in Table 2.3 & 2.4 and Annexure II.

- **Current Policy Scenario:** This scenario considers the effective implementation of prevailing/current agricultural policies in India. It assumes policy implementation rates across various interventions that help to achieve the intended ambitions of existing government policies.
- **Net Zero Scenario:** This scenario envisions a transformative outcomes characterized by accelerated adoption of existing and new agricultural policies beyond the Current Policy Scenario. Consequently, the pathway is framed around to identify those interventions which will improve farmers' income, farm productivity and strengthen climate change resilience with potential mitigation co-benefits.

The list of various such possible interventions and their corresponding mitigation co-benefits is provided in Table 2.3. Assumptions underpinning both scenarios (Table 2.4), were developed through an iterative, multi-stakeholder consultation process involving over 30 experts. These assumptions reflect historical rates of policy penetration, the ambition embedded within the current policy framework, and desirable future pathways. Any pathway-induced changes in production are translated into corresponding mitigation co-benefits.

The list of various such possible interventions is provided in Table 2.3.

Table 2.3: Policy typologies mapped against their potential mitigation co-benefits

Sl. No	Implementation pathway	Relevant schemes	Parameter of change	Primary outcomes achieved	Potential impacts on GHG emissions
	Sustainable agricultural production				
1	Sustainable yield intensification	Pradhan Mantri Krishi Sinchai Yojna (PMKSY); Micro Irrigation Fund; Sub-mission On Agriculture Mechanisation (SMAM); Rainfed Area Development	Enhance output per ha (kg/ha)	1. Farmer livelihood through enhanced farm incomes 2. Enhance food security 3. Building adaptive capacity of farmers against the impacts of climate shocks	Reduced emission intensity per ha (CO_2e/ha)
2	Crop diversification	Crop Diversification Programme (CDP)[10]; Horticulture Mission; Mission on Edible oils, Pulses and Nutri-cereals (millets)	1. Input efficiency (kg/ha or lt/ha) 2. Soil health enhancement 3. Climate resilience 4. Diversified plate (kcal restructuring)	1. Farm resilience against climate and market shocks 2. Farm profitability 3. Food and Nutritional Security of India	Reduced emission intensity per ha (CO_2e/ha)

10 Rashtriya Krishi Vikas Yojna (RKVY)

Sl. No	Implementation pathway	Relevant schemes	Parameter of change	Primary outcomes achieved	Potential impacts on GHG emissions
3	Cropping intensity	Pradhan Mantri Krishi Sinchayee Yojna (PMKSY-MI); Accelerated Irrigation Benefits Programme (AIBP)	Enhanced output (kg/ha/year)	1. Farmer livelihood through enhanced due unlocking more cropping cycles 2. Food security 3. No net increase in Net sown area	Reduced emissions per output (CO_2e/ kg)
	Sustainable Livestock Production				
4	Sustainable Yield Intensification (SYI)	National Livestock Mission (NLM); Ration Balancing Programme (RBP)	Enhanced milk output per animal per day (lt/day/ animal) Feed efficiency improvement (kgfeed/lt)	1. Enhanced income 2. Food and nutritional security 3. Adaptive capacity of farmers against shocks 4. Reduced overall animal population (millions)	Reduced emission intensity (CO_2e/ animal/ day)
5	Livestock health management	National Livestock Mission (NLM); Rashtriya Gokul Mission (RGM)	1. Enhanced reproductive health of livestock 2. Climate resilience (Singh et al, 2017)	1. Reduced costs of livestock maintenance at the farmer level, enhancing the profitability per herd	Reduced overall emissions from livestock
	Sustainable Agricultural Practices				
6	Natural and Chemical-free farming	National Mission on Natural Farming (NMNF); Paramparagat Krishi Vikas Yojna (PKVY); Soil health card scheme; PM–PRANAM; Green credits; Neem-coated urea	1. Input efficiency (kg/ha of L/ha) 2. Soil health (SOC) 3. Climate resilience 4. Agro-biodiversity	1. Long-term yield sustainability 2. Long-term livelihood security 4. Farm resilience 5. Nutritional security	Reduced nitrous oxide emissions from the reduction in application of chemical fertilisers
7	Enhance Fertiliser uptake/use efficiency (FUE)	Neam-coated urea; Integrated Nutrient Management (INM)	1. Input efficiency (kg input/ kg output) 2. Soil health protection 3. Overall reduction in the use of fertiliser	1. Long-term yield sustainability 2. Food security	Reduced nitrous oxide emissions per kg output, improving the emission intensity of production

Sl. No	Implementation pathway	Relevant schemes	Parameter of change	Primary outcomes achieved	Potential impacts on GHG emissions
8	Sustainable Rice Cultivation (SRC) practices	Bringing Green Revolution to Eastern India (BGREI)	1. Water use efficiency (lt/ha) 2. Water stress management 3. Climate resilience	1. Farm income stability 2. Climate resilience	Up to 59% reduction in methane emissions from rice fields (Annexure III)
	Circular Bioeconomy				
9	Agriculture Waste Burning	Crop residue management under RKVY[9]; BioE3 Policy	1. Diversified farm incomes 2. Climate action 3. Soil health management 4. Enhanced bioeconomy	1. Farmer livelihoods 2. Reduced air pollution	Reduced methane and nitrous oxide emissions from the burning of biomass

Table 2.4: Key assumptions for 2047 and 2070

Policy typology	Scenarios Number	Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
					2047	2070	2047	2070
1. Sustainable agriculture production	1.1	Cropping intensity	% GCA (ha)/ NSA (ha)	151	160	165	170	180
	1.2	Crop diversification away from rice, wheat and sugarcane	% area shifting from rice, wheat and sugarcane	0.23 (2019)	10	15	15	20
	1.3	Sustainable Yield Intensification (SYI)	% reduction in yield gap[11]	0 (66% yield gap)	15	20	40	70
2. Sustainable agriculture practices	2.1	Natural and Chemical-free farming	% net sown area	6	15	20	20	25
	2.2	Fertiliser uptake efficiency (FUE)	% of kg of nutrient uptake /kg of fertiliser applied	33	38	40	45	50
	2.3	Sustainable Rice Cultivation (SRC) practices	% of area under rice	0.25	10	20	18	25

11 Yield gap for crops is defined as the difference between the current attainable yield and the average yield achieved in India.

Policy typology	Scenarios Number	Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
					2047	2070	2047	2070
3. Sustainable livestock production	3.1	Enhanced in-milk bovine productivity	kg/head/day	5.27	8	12	12	15
	3.2	Share of the In-milk population	% in-milk in total bovine population	30	40	45	45	55
4. Circular bio-economy	4.1	Reduced burning of crop residue	% reduction in crop residue burnt	0	20	30	40	60

Note: *Annexure II contains a detailed policy mapping and assumptions behind the Scenarios presented in the above table.*

Each parameter shown in the table is described subsequently.

Scenario 1.1: Cropping Intensity

Cropping intensity refers to the number of crops grown on the same field during one agricultural year. Recent data shows that the national average cropping intensity in India is ~155% (Agriculture Statistics, 2023), meaning cropland is cultivated approximately 1.55 times annually. This represents a gradual increase from ~140% in the early 2010s (Sharma, 2023) due to the implementation of *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY) and *Rashtriya Krishi Vikas Yojana* (RKVY) since 2015.

Increasing cropping intensity boosts food production per unit area, increases farm incomes, and potentially reduces agriculture land expansion. Concurrent scaling of agroecology and soil management practices through *National Mission on Natural Farming* (NMNF), *Soil Health Cards* (SHC), and *Pradhan Mantri Krishi Vikas Yojna* (PKVY) is crucial to prevent risks of unsustainable intensification, notably soil degradation through over-fertilisation and water table depletion from over-extraction. Increasing cropping intensity is expected to lead to higher GHG emissions per hectare, but lower GHG emissions per output.

In the Current Policy Scenario, cropping intensity is projected to increase to 160% in 2047 and 165% in 2070. In Net Zero Scenario, it is projected to increase to 170% in 2047 and 180% in 2070 (Table 2.4a).

Table 2.4a: Assumptions of cropping intensity in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Cropping intensity	% GCA / NSA (in ha)	151	160	165	170	180

Scenario 1.2: Crop diversification

Mitigation "co-benefits" from the GoI's Crop Diversification Programme (CDP) under Rashtriya Krishi Vikas Yojana (RKVY), which has led to diversification of 1.02 lakh ha (0.102 Mha) away from water-intensive crops (rice and tobacco), stood at 0.214 MtCO2e between 2019-24 (MoEFCC, 2024).

Crop diversification is a strategy in which farmers shift away from rice, wheat, or sugarcane-dominated monoculture systems toward high-value crops (horticulture, oilseeds etc) or nutri-cereals crops as a climate adaptation strategy. This transition can enhance farm incomes by reducing risk and increasing value per hectare and enhance nutritional security (Barman et al, 2022). This transition also yields relative mitigation co-benefits, as Greenhouse Gas (GHG) emissions per hectare decline when farmers shift from input-intensive monoculture systems to more diversified cropping systems.

Crop diversification pathways must consider implications for food security and farm incomes, in both the short and long term. The analytical snapshot, given in Annexure VI, evaluates the feasibility of diversifying away from rice to nutri-cereals as an example, identifies potential leading states and outlines a short-term roadmap to facilitate this transition.

In the Current Policy Scenario, ~10% of the cropped area is assumed to be diverted from rice, wheat and sugarcane by 2047 and ~15% by 2070%. In Net Zero Scenario, the corresponding numbers are ~15% by 2047 and ~20% by 2070 (Table 2.4b).

Table 2.4b: Assumptions of area-based crop diversification in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Area-based crop diversification away from rice, wheat and sugarcane	% area shifting from rice, wheat and sugarcane	0.23 (2019)	10	15	15	20

Scenario 1.3: Sustainable Yield Intensification

Sustainable Yield Intensification (SYI) refers to enhancing crop productivity per unit of arable land through agronomic, ecological, and technological interventions without degrading environmental quality or depleting natural resources. In this report, Sustainable Yield Intensification (SYI) focuses on narrowing yield gaps relative to current realisable yields through technological upgrades and resource-efficient practices, including site-specific nutrient management and climate and stress-tolerant, high-yielding crop varieties promoted and developed under the *National Innovations in Climate Resilient Agriculture* (NICRA), among others. Given that yield gaps for major crops such as rice, wheat, maize, and sugarcane range between 66% and 75%, narrowing these gaps is critical to meeting rising food and biomass demands while addressing the "land squeeze" from competing uses such as bioenergy and fiber production.

In the Current Policy Scenario, ~20% yield gap will be bridged by 2070. In Net Zero Scenario, the corresponding scenarios are 70% by 2070 (Table 2.4c).

Table 2.4c: Assumptions of sustainable yield intensification in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Sustainable yield intensification (SYI)	% reduction in yield gap[12]	0 (66% yield gap)	15	20	40	70

Scenario 2.1: Natural and Chemical-free farming

Natural and Chemical-free farming encompasses agroecological practices that eliminate or replace synthetic chemical inputs with bio-based alternatives, relying on ecological processes to maintain soil fertility, manage pests, and sustain crop productivity. This report explores long- term scenarios for scaling the adoption of natural and chemical-free farming, focusing on natural[13] and organic farming systems[14], which currently cover 6% of India's Net Sown Area (NSA)[15]. The analysis is situated within key policy initiatives, including the *Paramparagat Krishi Vikas Yojana* (PMKY) and the *National Mission on Sustainable Agriculture* (NMSA). In light of recent policy momentum with the announcement of the *National Mission on Natural Farming* (NMNF), which aims to scale natural farming to ~7.5 lakh hectares of net sown area, Annexure VI (Part 2) presents a framework for scaling chemical-free practices. While large-scale adoption of natural farming and agroecological practices offers significant long-term environmental and cost benefits, perceived short-term yield risks under certain conditions may constrain adoption and must be carefully managed to safeguard food security (Kumar et al, 2020). As a result, under the Current Policy Scenario, natural and chemical-free farming, currently covering less than 5% of the net sown area, is assumed to expand to 20% by 2070, increasing further to 25% under the Net Zero Scenario by 2070) (Table 2.4d).

12 Yield gap for crops is defined as the difference between the current attainable yield and the average yield achieved in India.

13 Natural Farming is a system rooted in agroecological principles that integrates crops, trees and livestock with functional biodiversity. It is largely based on on-farm biomass recycling with major stress on biomass mulching, use of on-farm cow dung-urine formulations; maintaining soil aeration and exclusion of all synthetic chemical inputs. Natural farming is expected to reduce dependency on purchased inputs. It is considered as a cost- effective farming practice with scope for increasing employment and rural development.

14 Organic farming systems' focus is on using naturally available resources as inputs, such as organic wastes (crop, animal and farm wastes, aquatic wastes) and other biological materials along with beneficial microbes (biofertilisers/ bio control agents) to release nutrients to crops and protect them from insect pest and diseases for increased agricultural production.

15 Stakeholder consultations

Table 2.4d: Assumptions of chemical-free farming in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Natural and Chemical-free farming	% net sown area	6	15	20	20	25

Scenario 2.2: Fertiliser Uptake Efficiency

Mitigation "co-benefits" achieved through adoption of 134.05Mt neem-coated urea as a measure to improve FUE stood at 26.81 MtCO2e between 2019-24 (MoEFCC, 2024).

Fertiliser Uptake Efficiency (FUE) measures how effectively crops utilise applied fertilisers, and is calculated as the ratio of crop output to fertiliser used. In India, FUE has declined, with Nitrogen Use Efficiency (NUE) having dropped from 48% in the 1960s to 35% in 2018 (Singh, 2023) due to increased reliance on synthetic fertilisers. This report explores long-term scenarios for the likely effects of initiatives like Soil Health Management (SHM) and the mandate for 100% neem-coated urea to improve FUE. As a result, Fertiliser use efficiency is assumed to increase to 40% by 2070 in Current Policy Scenario and 50% by 2070 in Net Zero Scenario (Table 2.4e).

Table 2.4e: Assumptions of fertiliser uptake in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Fertiliser uptake	% of kg of nutrient uptake/kg of fertiliser applied	33	38	40	45	50

Scenario 2.3: Sustainable Rice Cultivation Practices

Mitigation "co-benefits" of the adoption of System of Rice Intensification (SRI) and Direct Seeded Rice (DSR) rice cultivation practices across 1.11 lakh ha (0.11 Mha) stood at 0.19 MtCO2e between 2019-24 (MoEFCC, 2024).

Sustainable Rice Cultivation (SRC) refers to agronomic practices that can enhance water efficiency and reduce input costs in paddy cultivation, which accounts for 40% of India's irrigation water use. Key techniques like Alternate Wetting and Drying (AWD), System of Rice Intensification (SRI), Subsurface Irrigation (SI), and Drip Irrigation (DI) can reduce water use by 30–40% while maintaining or improving yields. These practices also promote aerobic conditions in the paddy fields, reducing the methane emissions. This report models long-term scenarios for scaling Sustainable Rice Cultivation (SRC) given its strong water-saving potential and climate mitigation co- benefits. Annexure III contains the mitigation potentials of various SRCs in different states of India. Under the Current Policy Scenario, sustainable rice cultivation practices is assumed to increase to 20% of rice area by 2070 and under the Net Zero scenario the same will increase to 25% of rice area by 2070 (Table 2.4f).

Table 2.4f: Assumptions of sustainable rice cultivation practices in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Sustainable rice cultivation practices	% of area under rice	0.25	10	20	18	25

Scenario 3.1: Milk Productivity in Bovine Animals

Mitigation "co-benefits" of the adoption of the Ration Balancing Programme (RBP) stood at 0.0205 MtCO2e during 2019-24 for 1.63 lakh/163 thousand animals (MoEFCC, 2024)

Milk productivity refers to the average daily milk output of lactating animals. It is influenced by several interrelated factors such as quality and quantity of feed and fodder, genetic potential of the breed, animal health status, and regional agro-climatic conditions. Enhancing milk productivity is critical for growing milk production without a proportional increase in the bovine population. This, in turn, would moderate the sector's greenhouse gas emissions. Recent policy initiatives on animal health and nutrition, such as the *Ration Balancing Programme* (RBP), *Rashtriya Gokul Mission* (RGM) and the adoption of innovative feed additives like Harit Dhara, exhibit the potential to significantly increase milk yields across breeds.

Under the Current Policy Scenario, bovine productivity is assumed to increase from 5.27 to 12 kg/head/day by 2070 and 15 kg/head/day by 2070 in Net Zero Scenario (Table 2.4g).

Table 2.4g: Assumptions of enhanced in- milk bovine productivity in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Enhanced in- milk bovine productivity	kg/head/day	5.27	8	12	12	15

Scenario 3.2: Share of In-Milk Population

In-milk adult female bovine animals refer to those cows and buffaloes that are actively lactating and producing milk. The share of in-milk animals increases with a higher proportion of female bovines in the herd and, within this group, a greater proportion of animals in lactation. For the former, techniques like sex-sorted semen, which increase the probability of getting a female calf, can be explored. For the latter, enhancing animal breed quality, nutrition, and health can extend lactation periods, thereby improving the proportion of in-milk animals. Practices like deworming can further improve nutrient absorption and reproductive health, while regular vaccination can prevent reproductive infections (NAAS, 2013). Estrus detection and synchronisation techniques to ensure timely insemination significantly improve conception rates and reduce calving intervals (Mishra and Tiwari, 2014).

Under the Current Policy Scenario, in-milk bovine population is to assumed to increase in share from 30% in 2019 to 45% by 2070 and 55% by 2070 in Net Zero Scenario (Table 2.4h).

Table 2.4h: Assumptions of increasing share of the in-milk population in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Share of the In- milk population	% in-milk in total bovine population	30	40	45	45	55

Scenario 4.1: Reduced Crop Residue Burning

Mitigation "co-benefits" of the Crop Residue Management scheme (CRM) implemented under Rashtriya Krishi Vikas Yojana (RKVY) aimed to reduce crop residue burning through ex-situ management stood at 1.447 MtCO2e between 2019-24 (MoEFCC, 2024).

Crop residue refers to plant material, such as straw and stubble, that is left after harvesting. In some parts of the country, for certain crops, some of this residue is burned to quickly clear fields cost-effectively. This exacerbates air pollution and greenhouse gas emissions while wasting valuable biomass. India generates around 140 tonnes of surplus crop residue annually, of which 92 tonnes are burnt (Bhuvaneshwari,2019). This report estimates the percentage reduction in residue burning in the backdrop of the Crop Residue Management (CRM) scheme, exploring long-term scenarios for significant reductions by 2050 and near elimination by 2070.

Under the Current Policy Scenario, crop residue burning is to assumed to decrease by 30% in 2070 and 60% by 2070 in Net Zero Scenario (Table 2.4i).

Table 2.4i: Assumptions of reduced burning of crop residue in Current Policy Scenario and Net Zero Scenario (from Table 2.4)

Interventions	Unit	Current status for the baseline of 2019	Current Policy Scenario		Net Zero Scenario	
			2047	2070	2047	2070
Reduced burning of crop residue	% reduction in crop residue burnt	0	20	30	40	60

2.2 ENERGY DEMAND ESTIMATIONS FOR AGRICULTURE

The energy demand modelling framework consists of two modules: (i) irrigation pumping and (ii) land preparation, tracing the pathway from key drivers to final energy use based on the crop production projections.

1. **Irrigation Module:** estimates energy demand for pumping by linking crop demand projections with irrigation water requirements, pump stock and efficiency parameters As shown in Figure 2.2, the methodology starts with projected demand for major

crops, which is converted into total cultivated area and then split into irrigated and rainfed portions.

Irrigated crop area is transformed into irrigation water requirement using crop-specific water productivity (kg/m^3). In this study, only the pump-dependent share of this water is carried forward to estimate total energy demand for irrigation water pumping. Pumped water demand is converted into pump stock and finally into energy demand using assumptions on pump discharge, operating hours, dynamic head, technology mix, and pump efficiency,.estimates pumping energy demand by linking crop demand projections with irrigation water requirements, pump stock and efficiency parameters (Figure 2.2). A detailed methodology is given in Annexure IV.

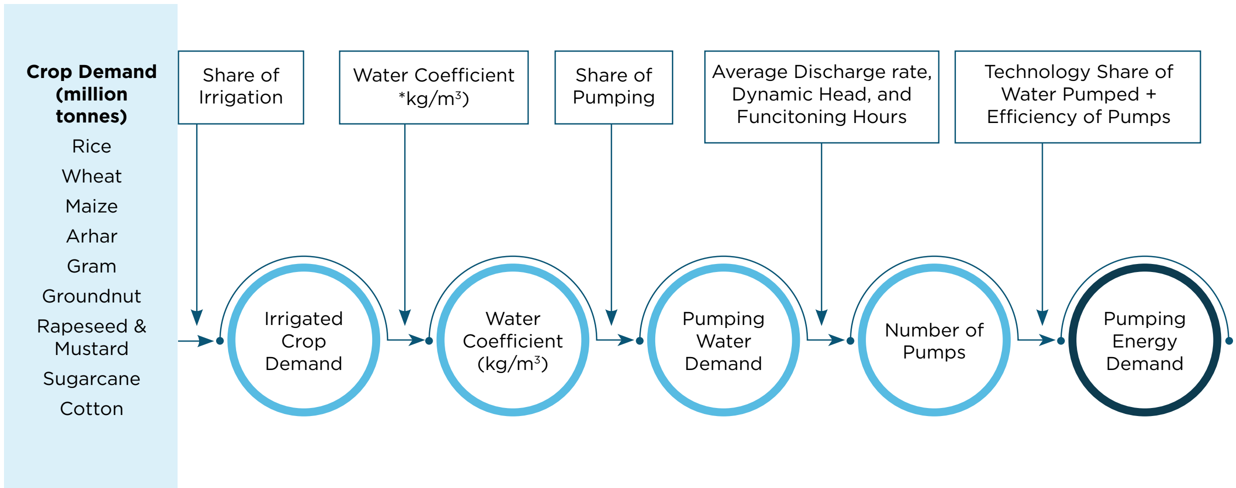

Figure 2.2: Irrigation module for energy demand projections

2. **Land Preparation Module:** As shown in Figure 2.3, Land-preparation energy demand is estimated by projecting Gross Cropped Area (GCA) and applying the assumed mechanisation rate to derive the area prepared using tractors and power tillers. This mechanised area is allocated between tractors and tillers using a conservative equivalent land-coverage assumption (tractor:tiller contribution based on operating-capacity conversion). Finally, specific energy intensity factors (operating hours/ha × fuel use/hour) are applied to each area segment and aggregated to obtain total final energy demand. A detailed methodology is given in Annexure V.

Figure 2.3: Land preparation module for energy demand projections

To analyse the long-term energy demand of India's agriculture sector, two alternate pathways are assessed up to 2070: Current Policy Scenario and Net Zero Scenario. Both scenarios assume the same crop production trajectories as developed in Figure 3.1, but differ in how this demand is met in terms of energy use.

Assumptions for Irrigation Energy Consumption

Irrigation is the dominant source of agricultural energy use. Under the Current Policy Scenario, irrigated share of cropped area rises steadily, groundwater dependence deepens, and diesel pumps decline only gradually. Pump efficiency improves slowly, and solar adoption remains limited. Under the Net Zero Scenario, in contrast, efficient irrigation practices (drip, sprinkler) reduce water demand substantially, diesel pumps are phased out by 2035, and solar pumps dominate by 2070 with much higher efficiencies (Table 2.5).

Table 2.5: Assumptions for estimating energy consumption for irrigation under Current Policy Scenario and Net Zero Scenario

Scenarios	2020	Current Policy Scenario (2070)	Net Zero Scenario (2070)	Notes
Irrigated share of Gross Cropped Area	53%	65%	60%	FAO (2021) notes that India already leads globally in irrigated area; future increases constrained by water stress.
Groundwater/ Pumping share	65%	65%	60%	India remains heavily groundwater-dependent in comparison to the US (15%) and China (40%). Net Zero Scenario assumes investments in canal systems and recharge.
Water Productivity Improvement		+10	+25%	Net Zero Scenario assumes large-scale drip/sprinkler adoption (Sharma et al, 2018) assuming that drip can halve water needs for sugarcane/vegetables.
Share of Solar Pumps	2%	40%	60%	Diesel pump phase out by 2040 in Current Policy Scenario and by 2035 in Net Zero Scenario.
Share of Electric Pumps	70%	60%	40%	
Pump efficiency (Solar & Electric)	36%	40%	50%	Reflects best practices (EMC 2018).
Pumping Head (metre)	28	50	35	Net Zero Scenario assumes aquifer recharge and efficiency to prevent sharp rise.

Assumptions for Land Preparation Energy Demand

Both scenarios assume full mechanisation by 2047, driven by rising rural wages and declining farm labour. Differences lie in the energy profile: under the Current Policy Scenario, electric tractors and tillers dominate with small amount of diesel and Compressed Natural Gas (CNG) even by 2070. While in the Net Zero Scenario, there is almost 100% shift toward electric tractors and tiller with higher share of tillers in land preparation compared to Current Policy Scenario. (Table 2.6).

Table 2.6: Assumptions for estimating energy demand for land preparation under Current Policy Scenario and Net Zero Scenario

Scenarios	2019	2070 Current Policy Scenario	2070 Net Zero Scenario	Notes
Mechanisation level	47%	100%	100%	Tillers gain share as smallholder mechanisation expands.
Tractor:tiller split	95:5	70:30	50:50	
Energy intensity per ha (MJ/ha) (% reduction in energy intensity)	Tractors:880 Tillers: 960	-20% by 2070	-40%	
Fuel Consumption in Land Preparation	100% diesel	9% diesel, 8% CNG, 83% electric	99% electric, 1% Compressed Natural Gas (CNG)/ Compressed Biogas (CBG)	Net Zero Scenario assumes large-scale adoption of e-tractors and clean fuel tech.

3

RESULTS

Results

3

As discussed in the Background, this section presents mitigation co-benefits and energy demand for the agriculture sector against the policy pathways. **The chapter is organised into two sections:** (i) non-energy emissions pathways and (ii) energy transition pathways. The non-energy emissions pathways cover crop and milk production projections, the resulting emissions trajectories and mitigation co-benefits. The energy transition pathways present the projected trends in energy consumption and demand for on-farm operations through 2070 under the Current Policy Scenarios (CPS) and the Net Zero Scenarios (NZS).

3.1 NON-ENERGY EMISSIONS PATHWAYS IN AGRICULTURE

This section presents long-term emissions trajectories for the agriculture sector, with a particular focus on emissions from rice cultivation, agricultural soils, and livestock (enteric fermentation and manure management). As outlined earlier, the analysis adopts a supply-side, production-linked modelling framework with 2019 as the baseline and assesses mitigation co-benefits under the Current Policy Scenario (CPS) and the Net Zero Scenario (NZS) for 2047 and 2070.

Accordingly, rice production is expected to increase from about ~121 million tonnes to 184 million tonnes (52%), while wheat to rise from ~109 million tonnes to ~178 million tonnest (63%). Maize is expected to record the fastest growth, expanding from ~30 million tonnes to ~106 million tonnes (~250%).

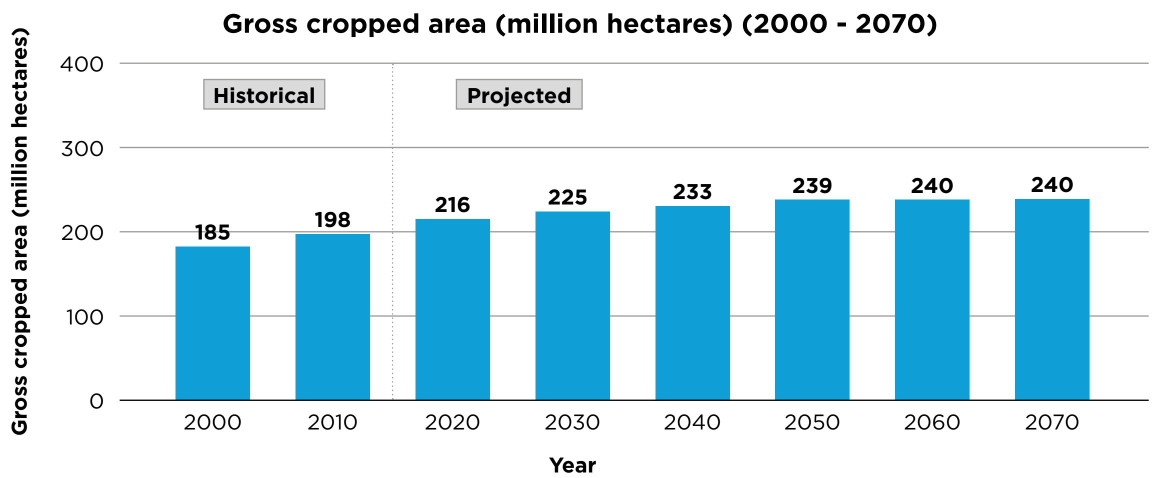

Figure 3.1: Gross cropped area projection (2000 to 2070)

In this analysis, food production projections do not directly determine land-use outcomes. Accordingly, Gross Cropped Area (GCA) projections are derived from historical trends (Figure 3.1). These two inputs are combined to derive overall fertiliser demand. Projections for organic nitrogen inputs similarly follow historical trends, consistent with India's submissions to the UNFCCC (MoEFCC, 2022).

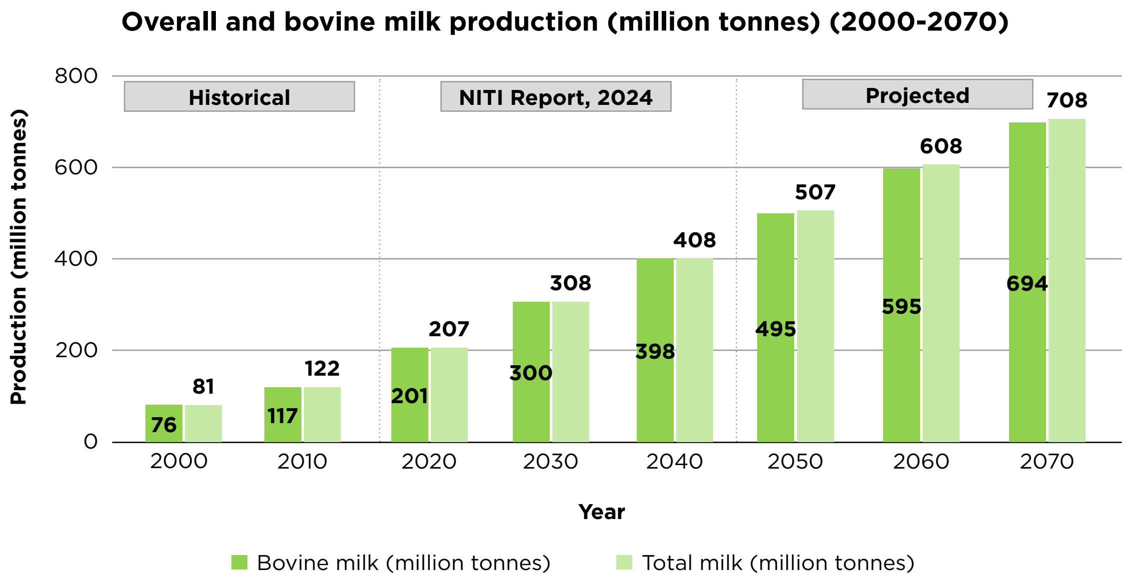

Figure 3.2: Production projections of bovine milk (2000-2070)

Figure 3.2 provide projections for milk that are based on trend-based approach, extrapolating historical trajectories from 2000 to 2070. This excludes goat milk, which accounts for approximately 4-5% of total milk output. Overall bovine milk is projected to increase from ~201 to ~694 million tonnes. This represents an increase of ~493 million tonnes, equivalent to a ~245% rise over the period, indicating more than a threefold expansion.

Long-term non-energy emissions pathways

Under the Current Policy Scenario (CPS), agricultural emissions are projected to increase modestly from ~506 in 2019 to ~531 $MtCO_2e$ by 2070. This aggregate trend masks diverging sub-sectoral trajectories. In the crop sub-sector, emissions (agricultural soils, rice cultivation, and residue burning) are expected to decline by ~21% from ~183 to ~145 $MtCO_2e$ (Figure 3.5). In contrast, livestock sub-sector emissions (enteric fermentation and manure management) are expected to rise by ~20% from ~322 to ~386 $MtCO_2e$ (Figure 3.4). Consequently, the crop sector's share of agricultural emissions falls from ~36% in 2019 to ~27% in 2070, while livestock's share increases from ~64% to ~73% by 2070 (Table 3.1).

In contrast to the Current Policy Scenario (CPS), under the Net Zero Scenario (NZS) total agricultural emissions are expected to decline to ~399 $MtCO_2e$ by 2070. This reduction is driven by a ~44% decline in crop sub-sector emissions and a modest decline ~8% decline in livestock sub-sector emissions. Overall, NZS delivers a ~25% mitigation co-benefit relative to CPS by 2070 (Figure 3.3; Table 3.1).

Note: In 2019, agricultural emissions were at 421 $MtCO_2e$ (AR2) which equals to 506 $MtCO_2e$ (AR5)[16].

Table 3.1: Agriculture emission trends across crop and livestock sub-sectors (2019 to 2070)

Year	Emission in Current Policy Scenario ($MtCO_2e$)			Emission in Net Zero Scenario ($MtCO_2e$)		
	Crop sub-sector	Livestock sub-sector	Total	Crop sub-sector	Livestock sub-sector	Total
2019	183	322	506	183	322	506
2050	156	379	535	116	286	402
2070	145	386	531	102	297	399

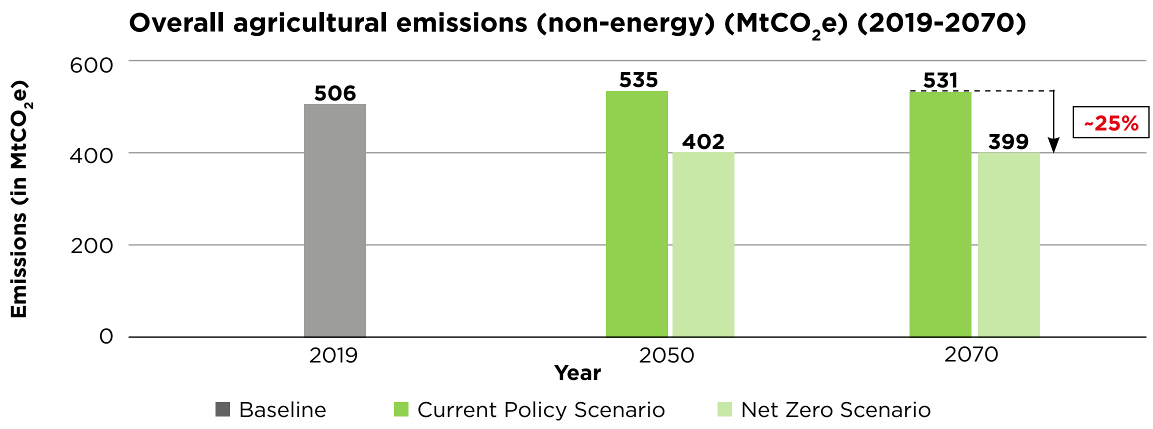

Figure 3.3: Projected agriculture emission under Current Policy Scenario and Net Zero Scenario (2019-2070)

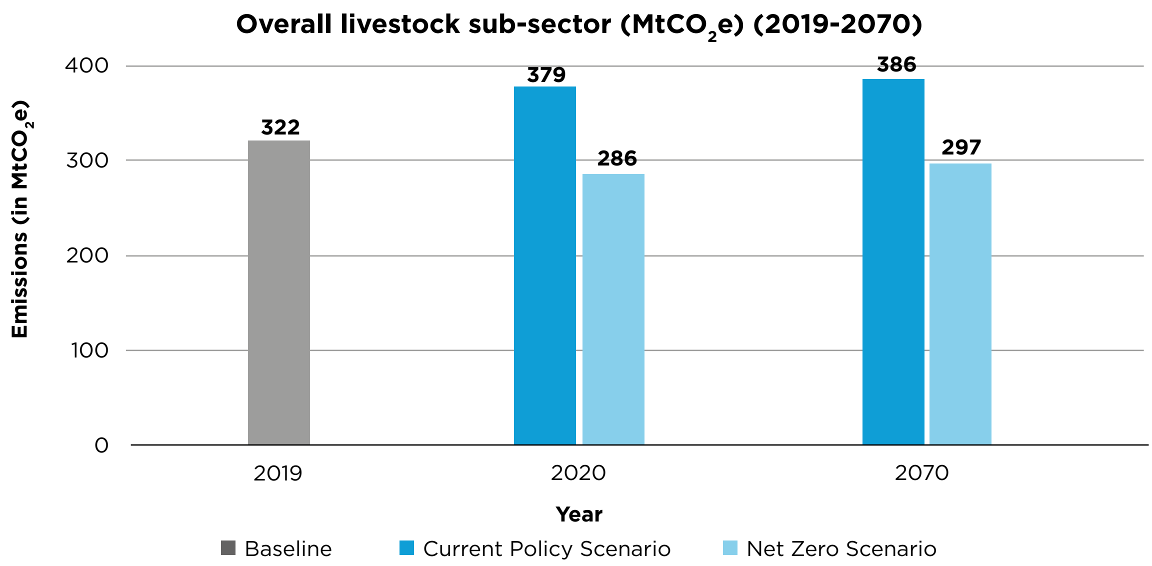

Figure 3.4: Overall emissions – Livestock sub-sector (2019-2070)

16 As per authors' analysis based on MoEFCC, 2021.

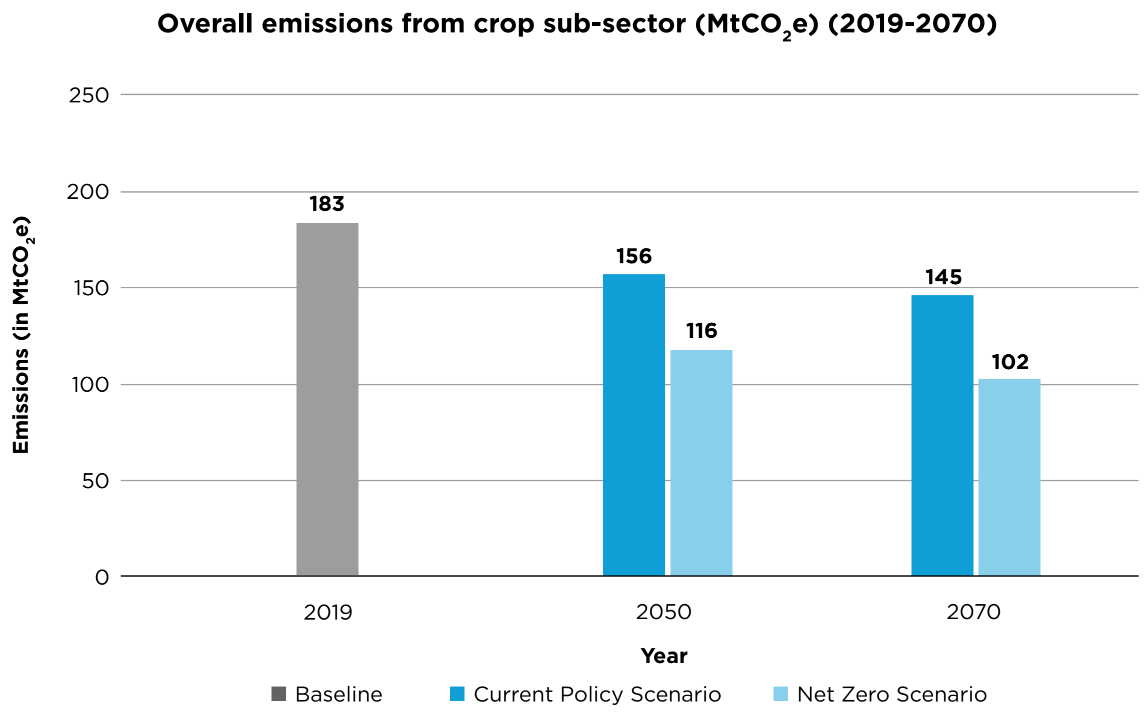

Figure 3.5: Overall emissions – Crop sub-sector (2019-2070)

The subsequent sections examine the key drivers of agricultural emission trajectories and their associated mitigation co-benefits. Understanding these drivers is crucial to identifying pathways that maximise mitigation co-benefits while delivering adaptation outcomes.

Methane emission from rice cultivation

The geographical concentration of rice mono-cropping in major producing regions such as Punjab, Haryana, and Western Uttar Pradesh has intensified water stress and degraded soil health. These regions also witness plateaued yields thereby, limiting farm profitability over the past two decades (NFSM, 2014). As Section 1.3 highlights, water-management practices have persisted in recent years. Key interventions to improve of rice cultivation in India include:

1. **Crop diversification** away from rice toward nutrient-dense, high-value alternatives.
2. **Sustainable yield intensification** through technological innovations, including high-yielding varieties.
3. **Adoption of sustainable rice cultivation practices** such as alternate wetting and drying (AWD), system of rice intensification (SRI), and direct-seeded rice (DSR).

Considering a coordinated scale-up of the above three interventions, the Net Zero Scenario (NZS) is projected to deliver ~47% mitigation co-benefits against that of the Current Policy Scenario (CPS) in 2070. Under the CPS, methane emissions from rice cultivation are projected to decline by ~30%, from ~98 $MtCO_2e$ in 2019 to ~69 $MtCO_2e$ by 2070. In the NZS, emissions decrease further to ~37 $MtCO_2e$, corresponding to a ~62% decline from 2019 (Figure 3.6).

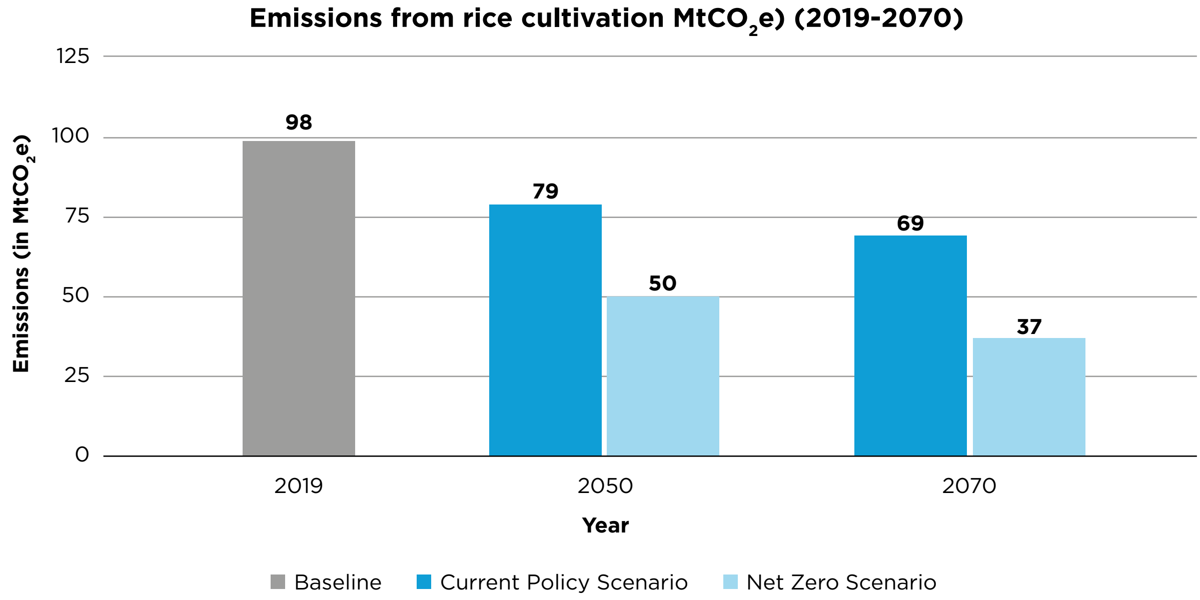

Figure 3.6: Rice cultivation emission trends in Current Policy Scenario and Net Zero Scenari (2019-2070)

Under Current Policy Scenario (CPS), rice acreage is expected to decline from ~44 to ~37 million hectares, by 2070. Almost ~20% area is expected to adopt sustainable rice cultivation (SRC) practices in the same period (Figure 3.7). Diversifying ~15% of the area and closing ~20% of the yield gap raises average yields from 2.7 t/ha to 3.8 t/ha, allowing production to increase from 119 million tonnes to ~133 million tonnes (Figure 3.9) despite a ~16% reduction in cultivated area (Figure 3.9).

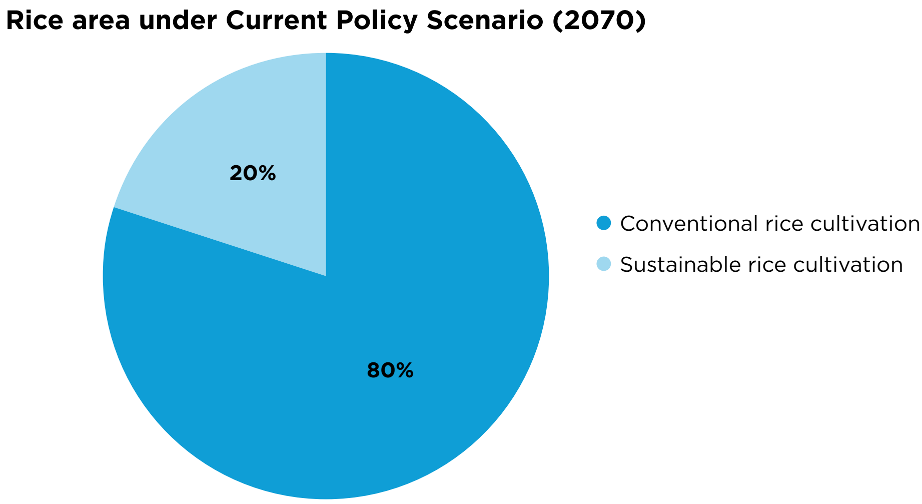

Figure 3.7: Area under rice cultivation in Current Policy Scenario (2019-2070)

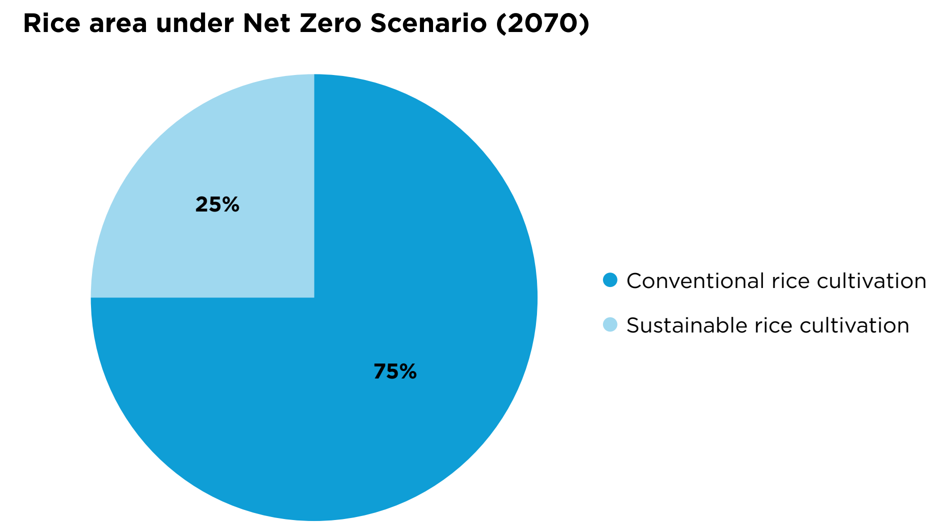

Figure 3.8: Area under rice cultivation in Net Zero Scenario (2019-2070)

Under the Net Zero Scenario (NZS), interventions are more ambitious. Rice acreage is expected to decline to ~20 million hectares, with sustainable rice cultivation (SRC) practices covering 25% of rice area (Figure 3.8) by 2070. Diversifying ~20% of the area and closing ~70% of the yield gap[17], will sustain production at ~126 million tonnes (Figure 3.9). The modest production increase mirrors India's population increase and the declining per capita rice consumption, consistent with broader dietary diversification (FAO, 2024). Together, these measures account for the significant mitigation co-benefits under both the scenarios without comprising on food security of India (Figure 3.9).

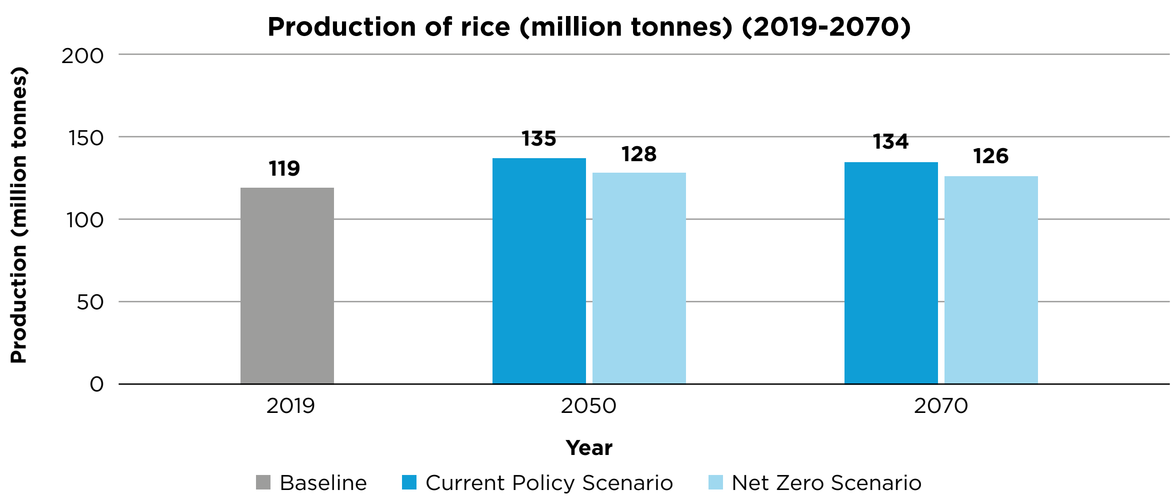

Figure 3.9: Rice production from 2019 to 2070 under Current Policy Scenario and Net Zero Scenario Rice area (2019-2070)

17 Projected yield in 2070 is ~7.6 t/ha.

Nitrous oxide emissions from Agricultural soils

Higher fertiliser application rates increase manufacturing demand, contribute to rising import dependence, and impose a fiscal burden of subsidies exceeding ₹2 lakh crore, while also degrading soil health (Singh, 2023). To address these challenges, India has implemented interventions to improve fertiliser use efficiency (FUE) through reduced application, soil health management, promotion of sustainable agricultural practices among others. At the same time, policies aimed at increasing cropping intensity and enabling additional cropping cycles are expected to raise aggregate nitrogen fertiliser consumption, partially offsetting the gains.

Under both the Current Policy Scenario and the Net Zero Scenario, these interacting dynamics: improvements in FUE reflected in lower per-hectare application rates, adoption of sustainable practices such as natural farming/organic farming (chemical-free farming), and the countervailing effects of higher cropping intensity, are jointly modelled to assess long-term agricultural soil emission trajectories.

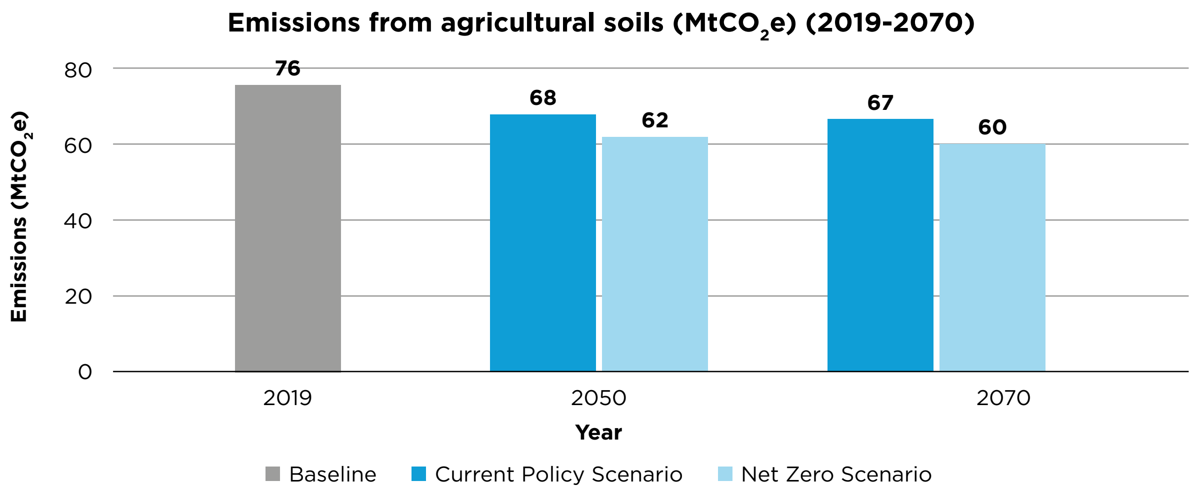

Figure 3.10: Agricultural soil emission trends in Current Policy Scenario and Net Zero Scenario (2019-2070)

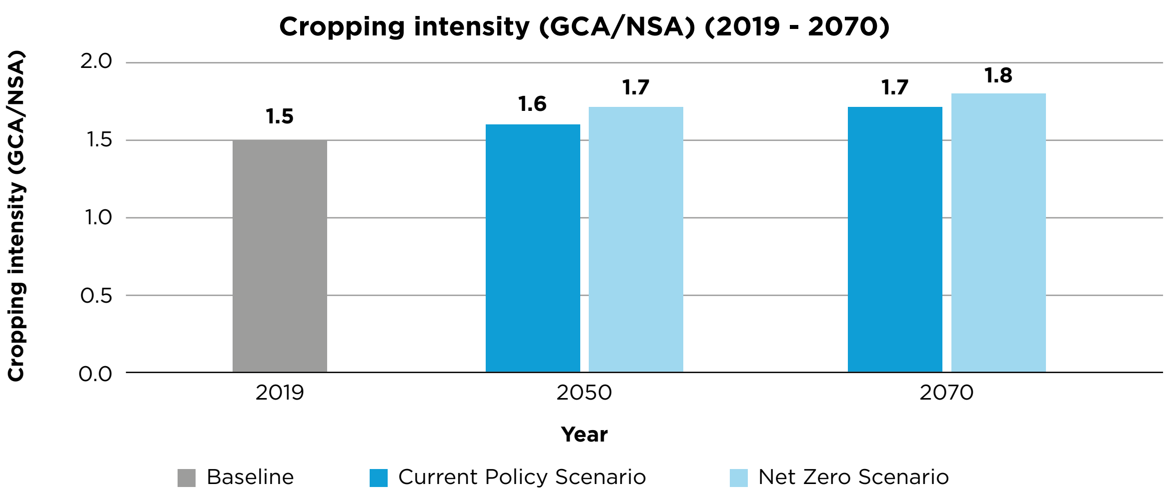

Figure 3.11: Cropping intensity in Current Policy Scenario and Net Zero Scenario (2019-2070)

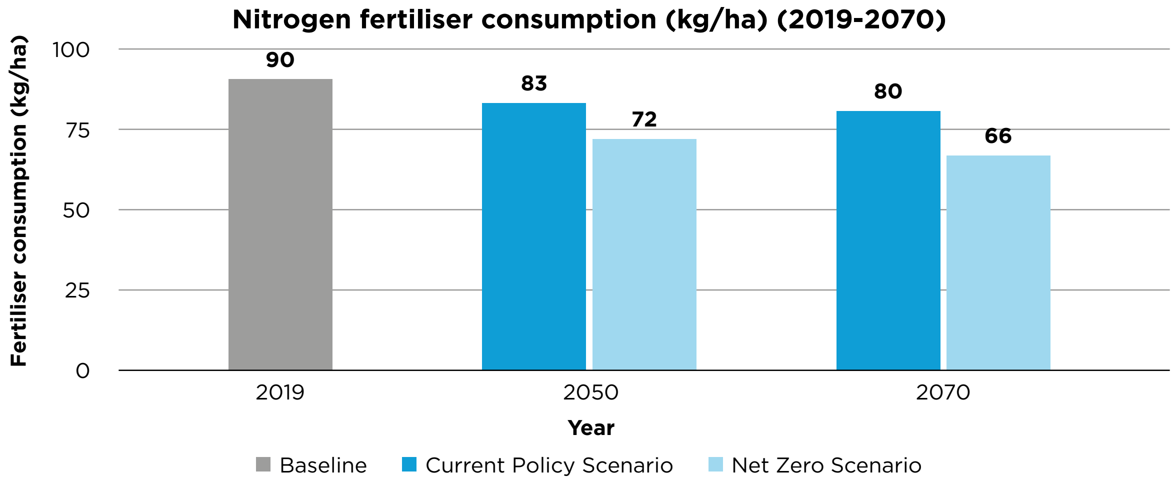

Figure 3.12: Nitrogen fertiliser consumption per ha in Current Policy Scenario and Net Zero Scenario (2019-2070)

Under the Current Policy Scenario (CPS), these measures are projected to deliver ~11% mitigation co-benefits, reducing emissions from ~76 $MtCO_2e$ in 2019 to ~67 $MtCO_2e$ by 2070 (Figure 3.10). This outcome reflects improvements in fertiliser use efficiency, which lower nitrogen application rates from 90 kg/ha in 2019 to 80 kg/ha by 2070 (Figure 3.12). At the same time, the expansion of natural and chemical-free farming is projected to increase to 28 million hectares (20% of NSA) (Figure 3.13). This reduces total nitrogen fertiliser demand in India from 19 million tonnes in 2019 to 15 million tonnes in 2070, even as cropping intensity increases (Figure 3.11).

Similarly, under the Net Zero Scenario, emissions from fertiliser use are expected to decline further to 60 $MtCO_2e$ by 2070 (~20% reduction), providing an additional 10% of mitigation co-benefit relative to Current Policy Scenario (Figure 3.10). This is achieved through wider adoption of natural and chemical-free farming practices upto 25% of Net Sown Area (Figure 3.13), lowering nitrogen application rates due to improved fertiliser use efficiency (~50% by 2070).

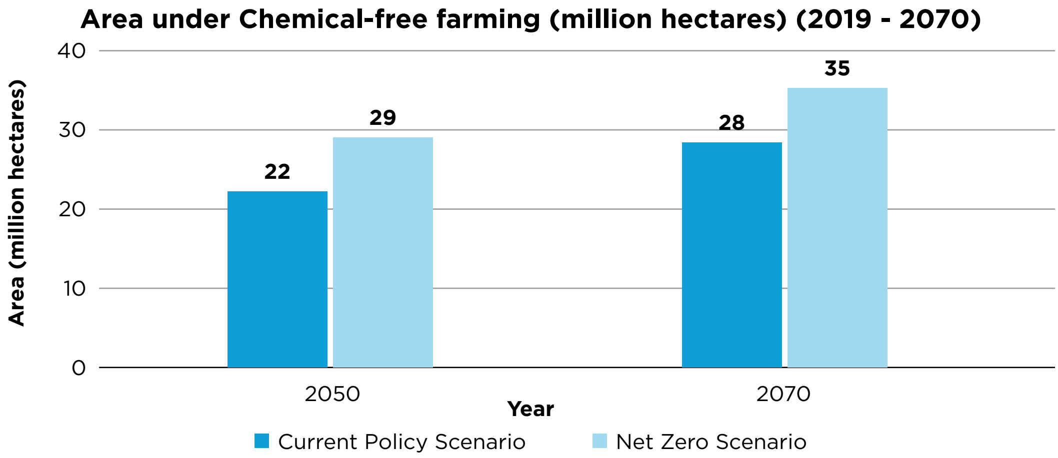

Figure 3.13: Area under Natural and Chemical-free farming Current Policy Scenario and Net Zero Scenario

Note: *Agricultural soil emissions are also sensitive to crop diversification, particularly shifts from rice to high-input crops like horticulture. Currently, nitrogen use per hectare is estimated at the aggregate level, but integrating crop-wise fertiliser data from the All-India Input Survey 2016–17 could improve future sensitivity analyses.*

Realising the Net Zero Scenario (NZS) requires careful, calibrated scaling of key interventions. *Integrated Nutrient Management* (INM) under the *National Mission for Sustainable Agriculture* (NMSA) and digital Soil Health Cards optimize nutrient application and maintain soil health. Mandatory consumption of 100% neem-coated urea reduces nitrogen volatilisation losses. Scaling chemical-free farming under *National Mission on Natural Farming* (NMNF) and *Pradhan Mantri Krishi Vikas Yojna* (PMKVY) must be implemented strategically to protect food security and farmer incomes, while transitioning millions of hectares to low-input, sustainable cultivation.

Livestock emissions

India is the world's largest producer of milk and contributes to ~25% of global milk output (PIB 2024). Milk production is projected to grow to ~467 million tonnes in 2050 and ~693 million tonnes in 2070, cumulatively rising by ~245% since 2020.

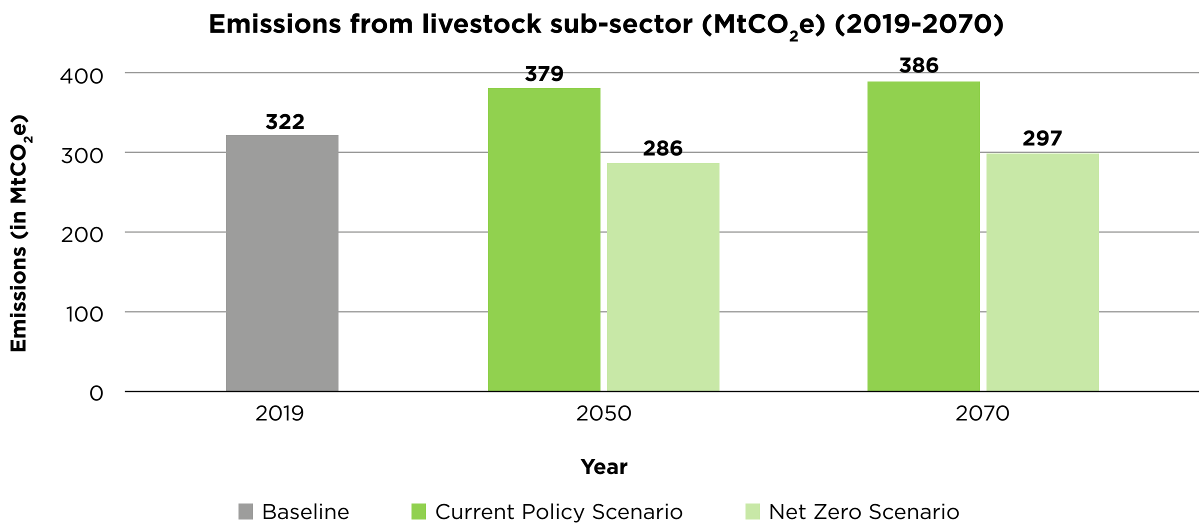

Figure 3.14: Emissions from livestock sector in Current Policy Scenario and Net Zero Scenario (2019-2070)

Under the Current Policy Scenario (CPS), livestock emissions are projected to rise from ~322 $MtCO_2e$ in 2019 to ~386 $MtCO_2e$ by 2070 (~20% increase) (Figure 3.14), with average in-milk productivity expected to reach 12 kg/day per animal (Figure 3.15). In contrast, the Net Zero Scenario (NZS) reduces emissions to ~297 $MtCO_2e$ by 2070 (~8% below 2019 levels) (Figure 3.14), while boosting productivity to 15 kg/day per animal (Figure 3.15). Within the herd, the proportion of in-milk animals rises from 35% in 2019 to 50% in 2070, supporting higher milk yields (Figure 3.16).

The Net Zero Scenario achieves ~23% mitigation co-benefits in the livestock sector through technological and management interventions. Yield improvements are driven by breed and genetic enhancements via programs like the *Nationwide Artificial Insemination Programme* (NAIP), alongside advanced breeding technologies, including in-vitro fertilisation (IVF). Additionally better nutrition through the *Ration Balancing Programme* (RBP), and year-round availability of green fodder using silage and roughage technologies further help to enhance productivity.

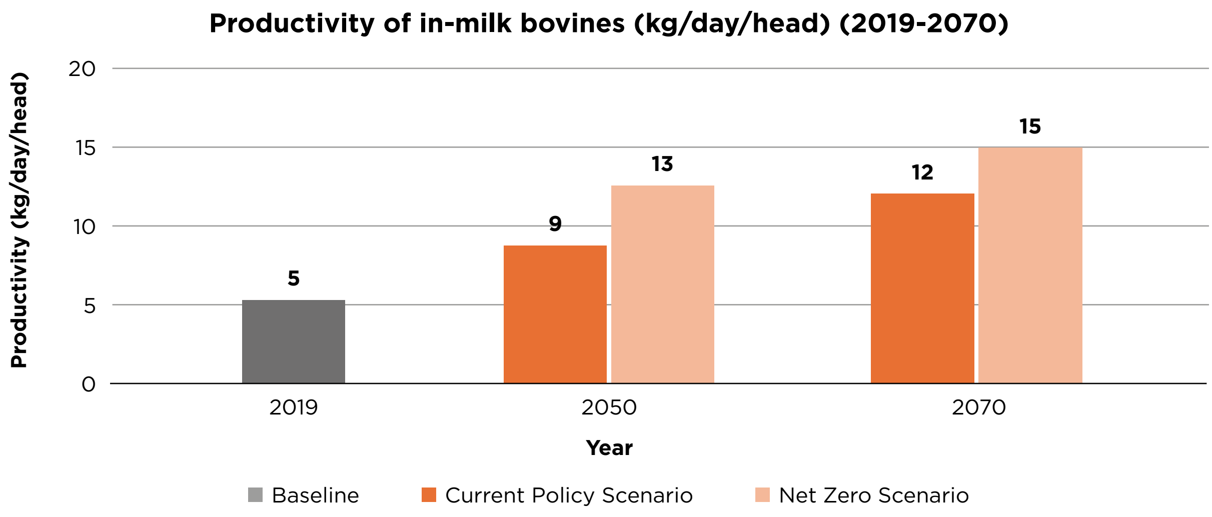

Figure 3.15: Milk yield trends in Current Policy Scenario and Net Zero Scenario (2019-2070)

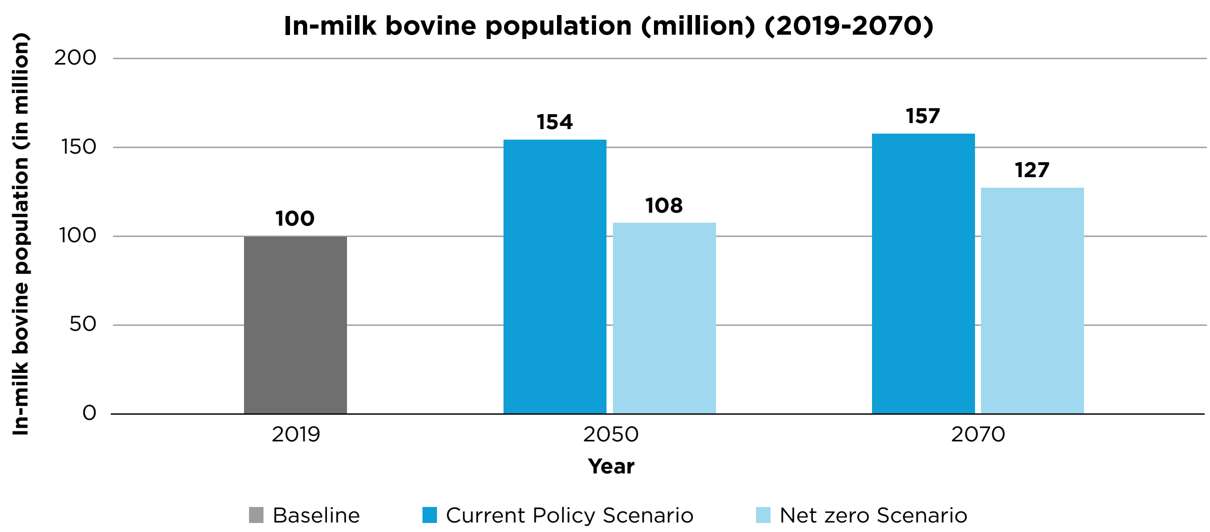

Figure 3.16: Share of in-milk bovine population in the total bovine population (2019-2070)

3.2 ENERGY EMISSIONS PATHWAYS IN AGRICULTURE

In 2020 India's agriculture consumed ~23 Mtoe of direct energy, 21 Mtoe for pumping (mostly electricity and diesel) and 2.1 Mtoe for land preparation (primarily diesel for tractors and tillers) (CEA, 2022). Under Current Policy Scenario (CPS), the total energy consumption in agriculture is expected to increase to 42 Mtoe by 2050 and 54 Mtoe by 2070. Under the Net Zero Scenario (NZS) also, the total energy use increases to 35 Mtoe by 2050 and 39 Mtoe by 2070. However, the total energy use in NZS is lower than the corresponding numbers for CPS. During the corresponding period, the agricultural output has nearly doubled. This shows that efficiency gains and technology shifts can decouple energy demand from agricultural output (Figure 3.17).

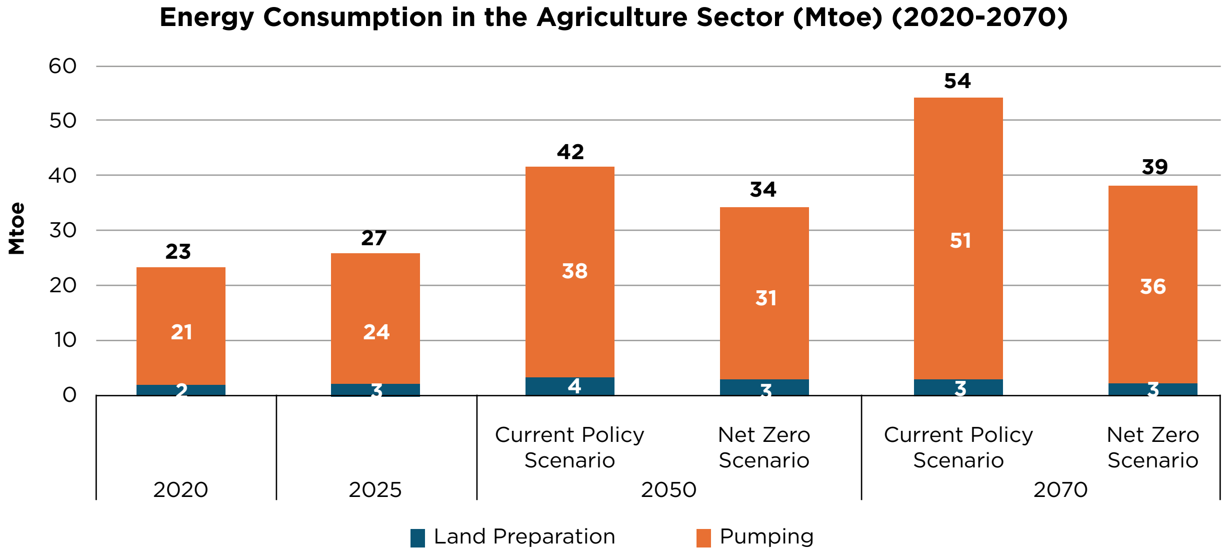

Figure 3.17: Overall energy consumption in Agriculture Sector (2020-2070)

Energy consumption in irrigation

Under Current Policy Scenario, energy demand rises from 21 Mtoe in 2020 to 38 Mtoe in 2050 and 51 Mtoe by 2070, driven by expanding irrigation (from 53% to 65% of GCA) and higher groundwater reliance (Figure 3.18a). Diesel pumps decline slowly, while grid electricity remains primary, complemented by solar pumps (40% of energy by 2070). Modest efficiency gains (40%) and deeper pumping heads (50 m) sustain high energy demand.

In Net Zero Scenario, pumping rises more moderately from 21 to 32 Mtoe by 2050, plateauing at 36 Mtoe in 2070 (Figure 3.18a). Efficiency improvements, adoption of drip/sprinkler irrigation, aquifer recharge, and better management limit energy growth. Diesel pumps are phased out by 2035, with 40% grid electricity and 60% solar supplying pumping energy by 2070 (22 Mtoe).

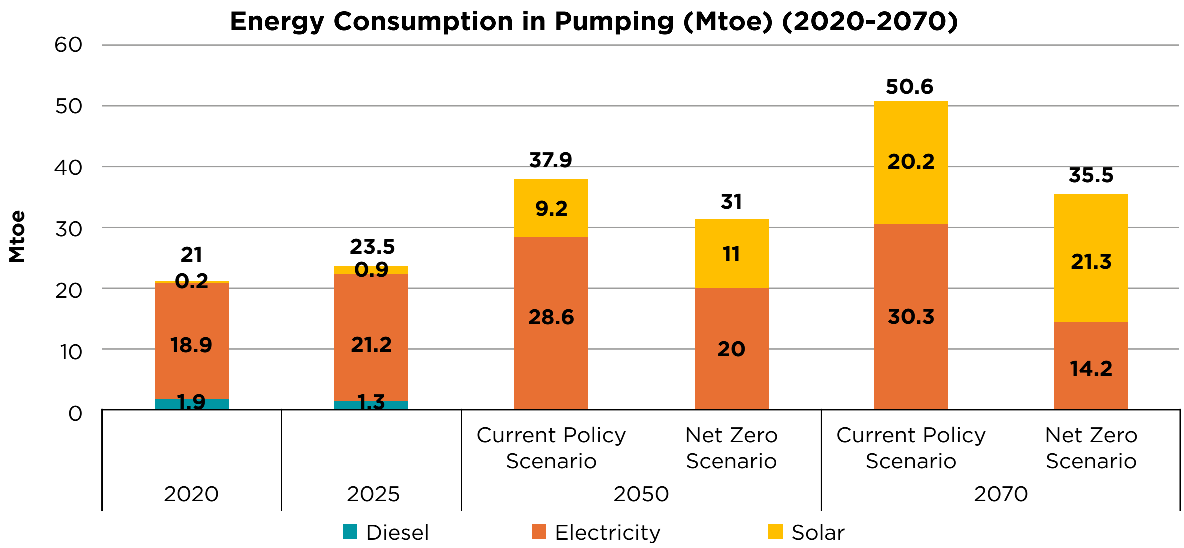

Figure 3.18a: Energy demand and fuel mix in agricultural pumping under Current Policy Scenario (CPS) and Net Zero Scenario (NZS) by 2050 and 2070

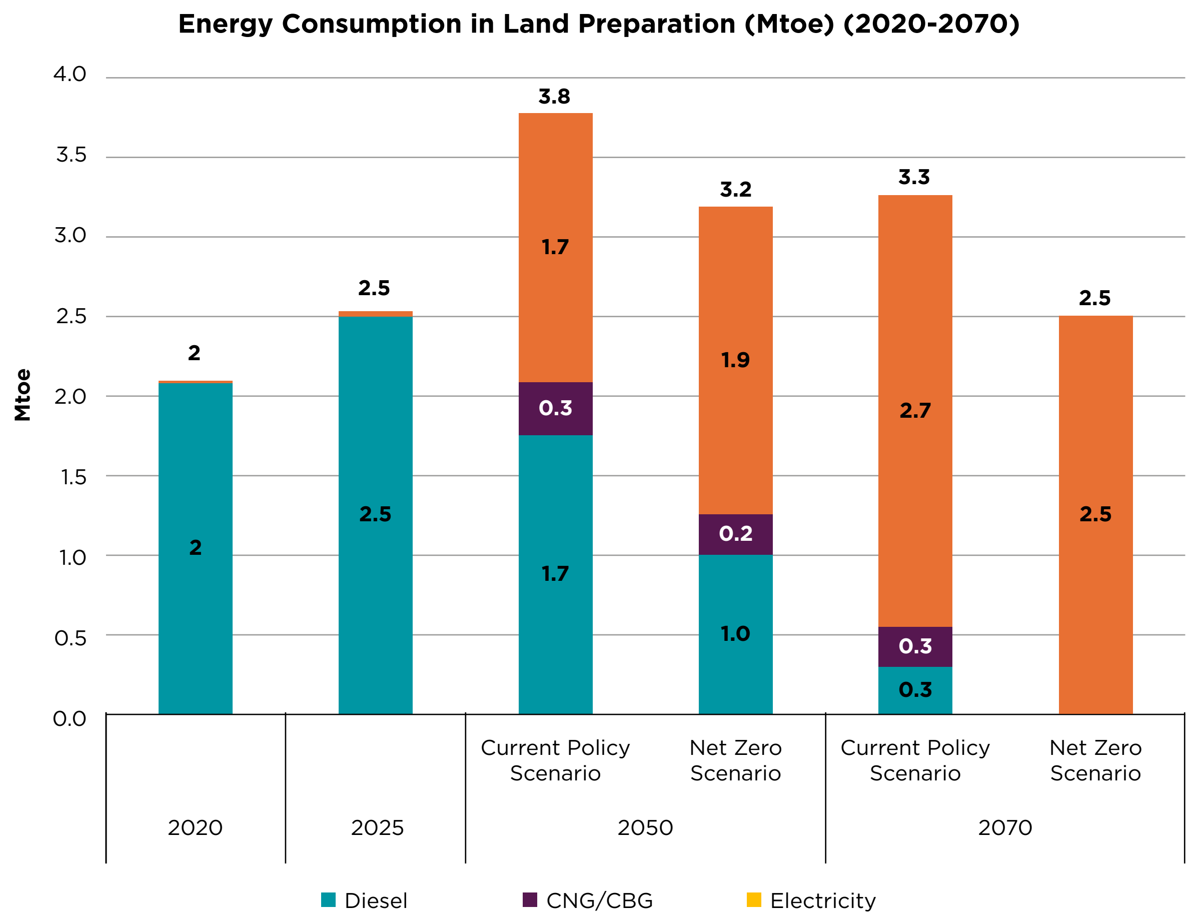

Figure 3.18b: Energy demand and fuel mix in land preparation under Current Policy Scenario (CPS) and Net Zero Scenario (NZS) by 2050 and 2070

Energy consumption in land preparation

Under the Current Policy Scenario (CPS), energy demand rises from 2.1 Mtoe in 2020 to 3.8 Mtoe in 2050 and 3.3 Mtoe by 2070, with 9% comming from diesel and 8% from CNG by 2070 (Figure 3.18b). Efficiency gains and precision agriculture reduce per-hectare fuel use, but expanding mechanisation drives overall demand.

Under Net Zero Scenario, total energy stabilises at ~2.5 Mtoe by 2070 despite full mechanisation (Figure 3.18b). Diesel is fully phased out by 2070, replaced by electric tractors and tillers (~2.5 Mtoe) with just 1% Compressed Biogas (CBG), sourced from crop residues and animal waste, acts as a transitional fuel in the 2040s, supporting India's *Sustainable Alternative Towards Affordable Transportation* (SATAT) initiative, reducing residue burning, and generating rural income. In the later decades, electric tractors dominate, offering ~30% higher efficiency and integration with a decarbonised grid and solar charging.

Box 3: State-Level Transitions in Practice

Gujarat – The Suryashakti Kisan Yojana (SKY) has shown how decentralized solar pumps connected to the grid can displace diesel, reduce subsidy costs, and even create new income streams as farmers sell surplus electricity. Farmers in Dhundi village, for example, have eliminated dozens of diesel pumps and now treat solar power as a secondary crop.

Rajasthan – In Rajasthan, drip irrigation coupled with solar pumps has enabled farmers to sustain yields while cutting water and energy use by 30–50%. This exemplifies the water–energy efficiency nexus modeled in the Net Zero Scenario.

Maharashtra – Maharashtra's feeder solarization programme demonstrates how centralized solar generation can deliver daytime electricity to thousands of pumps simultaneously. By 2025, the state targets 30% solarized feeders, reducing dependence on coal-based power. Taken together, these cases illustrate that the modeled Net Zero Scenario is not abstract.

The combination of efficiency (Rajasthan), decentralized solar (Gujarat), and feeder-level solarization (Maharashtra) shows how India can achieve plateauing energy demand despite rising output, while lowering fiscal and environmental costs.

4

KEY CHALLENGES AND SUGGESTIONS

Key Challenges and Suggestions

4

4.1 KEY CHALLENGES

The transition of India's agriculture and allied sectors from the Current Policy Scenario (CPS) to ambitious Net Zero Scenario (NZS) faces complex, interconnected structural challenges, despite the NZS offering a ~25% mitigation co-benefit by 2070 compared to the CPS trajectory. As a result, achieving the mitigation co-benefits in NZS require addressing many issues:

1. **Effectively managing trade-offs while harnessing synergies across livelihoods, resilience, and food security is critical to implementing Net Zero Scenario pathways:** For instance, adopting chemical-free practices, such as Natural Farming, can increase the availability of diverse and nutrient-rich foods, improving both public health and environmental quality by reducing agrochemical runoff and soil degradation. On the other hand, it may lower yields in the green revolution regions in the short term while possibly increasing them in the rainfed regions. The scaling up thus needs to be well planned to keep the food grain supply stable for India's food security. Balancing these competing and complementary objectives is critical. Hence, developing evidence-backed long-term strategic roadmaps is critical for a risk-calibrated approach to implementing the Net Zero Scenario (NZS) pathways.

   Driving the intervention identified under the Net Zero and Current Policy Scenarios feasibly needs comprehensive, long-term scaling strategies that are context-specific, targeted, and phased to capture synergies and balance trade-offs. For instance, as exemplified in Annexure VI (Part-1), scaling crop diversification requires a phased approach that targets states based on yields, biophysical suitability, and the capacity of public procurement channels, while safeguarding national food and nutrition security. Scaling animal health and nutrition interventions to boost milk productivity must account for contextual realities, such as state-specific breed composition, feed consumption patterns among various breeds, socioeconomic drivers of bovine rearing, and climate resilience of the whole bovine economy.

2. **Inherent affordability and access barriers for scaling adoption:** Agri-food systems face constrained adoption of technologies, mechanisation, particularly among small and marginal producers who struggle with affordability and last-mile access. These constraints are compounded by under capacitated support services, across extension, credit, insurance, market linkages, and post-harvest systems, that fail to enable a smooth transition to resilient and diversified practices. Further, significant gaps in timely, reliable, and localised data limit evidence-based decision-making for producers, value-chain actors, and policymakers alike.

Addressing these barriers requires a systemic overhaul of the enabling ecosystem that connects farmers and consumers. This includes stronger investments in research and development, deeper technology penetration, and the creation of targeted, responsive, and dynamic Krishi Decision Support Systems such as being done through the Agri-Stack. Improved market intelligence and transparent, well-designed incentive disbursement mechanisms will be essential to drive widespread adoption of sustainable agri-food practices.

This exercise of supply-side modelling that has generated pathways, is a critical first step towards informing long-term planning for the agriculture sector. However, translating the emission pathways into policy and planning frameworks requires feasible and targeted roadmaps. An agri-food systems approach delivers this required integrated perspective, which is essential for maximising agriculture's contribution to long-term livelihoods development, nutrition and health enhancement, resilience-building, as well as climate mitigation co-benefits.

3. **Managing trade-offs and leveraging land–energy–water synergies:** The Net Zero Scenario implementation must balance food security, water sustainability, clean energy deployment, and fiscal outcomes. Mechanisation and electrification without subsidy and groundwater reforms risk increasing power demand and utility stress, while large-scale solar raises land-use competition. Integrated approaches, combining solar irrigation, micro-irrigation, electric machinery, and agrivoltaics offer strong synergies but require coordinated, cross-sectoral planning. Institutional silos and fragmented governance must be resolved.

4. **Rising energy demand from irrigation pumping and groundwater dependence:** Irrigation energy demand continues to grow due to increasing cropping intensity, deeper groundwater tables, and climate-induced variability in rainfall. Even with solarisation, pumping loads may rise if water use remains unmanaged, limiting net energy savings. Weak regulation of groundwater extraction and limited adoption of efficient irrigation technologies compound this challenge. Managing pumping demand is therefore central to achieving durable mitigation outcomes.

5. **Energy-intensive land preparation and slow transition from diesel equipment:** Land preparation remains heavily reliant on diesel-powered tractors and tillage equipment, contributing significantly to on-farm energy use and emissions. While electric and Compressed Biogas (CBG)-based alternatives are emerging, adoption is constrained by high costs, limited charging or fuel infrastructure, and concerns over reliability during peak seasons. Without targeted support and shared-access models, diesel lock-in in land preparation risks persisting well into the transition period.

6. **Behavioural Inertia Across Producers and Consumers:** Deep-rooted production and consumption habits limit shifts toward diversified, nutritious, and sustainable food systems. Producers remain anchored to familiar cropping patterns due to risk aversion and market uncertainties, while consumers continue to prefer staple-heavy diets despite the availability of healthier alternatives. This is exacerbated by the absence of strong, integrated demand–production signals. Currently, fragmented many incentives work at cross-purposes. This reinforces existing production patterns and slows the transition to diversified, sustainable production systems. Addressing demand-side drivers and

barriers is far more critical: fostering dietary diversification (demand) enables shifts in cropping patterns (supply) and unlocks greater mitigation potential than pure supply-side measures (Jha et al., 2023; Patange et al., 2024).

For instance, mainstreaming millet consumption through public procurement channels (e.g., the Public Distribution System) and high-visibility initiatives like the International Year of Millets and India's Millet Mission can stimulate consumer demand, incentivising farmers to shift cultivation away from emission-intensive crops like rice. In addition, unlocking market potential, both domestic and global, is crucial to sustaining the production trajectory. For instance, milk exports have expanded notably over the past decade, yet boosting global competitiveness remains a challenge, constrained by quality standards, trade barriers, and logistical inefficiencies.

4.2 SUGGESTIONS FOR SUSTAINABLE LONG-TERM PATHWAYS FOR AGRICULTURE AND ALLIED SECTORS

This analysis demonstrates that the proposed Net Zero Scenario yields a ~25% mitigation co-benefit against the Current Policy Scenario. The finding is based on nine key interventions developed under multi-benefit centered, policy-driven assumptions. Interventions refined through rigorous, multi-stakeholder consultations highlight that there is both the need and feasibility of a systemic transformation within the sector that also comes with significant mitigation co-benefits. As a result, the following framework is proposed to accelerate an agri-food systems transformation for resilience, farmers' incomes and food security that deliver mitigation co-benefits:

1. **Develop long-term and short-term strategies to scale multi-benefit interventions:**

   Realising mitigation co-benefits requires ambitious yet feasible, risk-calibrated scaling of multiple interventions. This calls for a careful assessment of opportunities, trade-offs, social acceptance, and financial viability to avoid negative spillovers while safeguarding food security and livelihoods. This report therefore suggest intervention-specific roadmaps to maximise co-benefits and minimise trade-offs, as outlined in the following section:

   a) **Crop diversification:** India's crop diversification programme under *Rashtriya Krishi Vikas Yojna* (RKVY) has promoted shifts from water-intensive rice cultivation in Green Revolution states since 2015. Yet these regions still dominate national rice production. Achieving a 20% reduction in rice cultivation area by 2070 demands pragmatic interventions (technological, economic, and institutional) supported by geographically sensitive and temporally phased roadmaps that strategically enable:

      i. **Supply-side diversification:** Promote diversification through crop alternatives, such as pulses, millets, oilseeds, and horticultural crops, leveraging the Government of India's flagship missions.

      ii. **Demand-side linkages and diet diversification:** Ensure production shifts are complemented by strong demand signals. This includes integrating pulses and millets into the Public Distribution System (PDS), to create assured market linkages that drive consumption shifts. These efforts, as they enable integrated production- consumption shifts, must be guided by socio-economic assessments that align geographical diversification priorities with household-level nutrition and affordability considerations.

As outlined in Annexure VI (Part-1), strategically bundling and sequencing the above supply and demand side interventions will be critical to realising crop diversification, without undermining the food system security or farmer livelihoods.

b) **Natural and Chemical-free farming:** India has initiated several efforts to promote natural and chemical-free farming, including the *National Mission on Natural Farming* (NMNF), *Paramparagat Krishi Vikas Yojana* (PKVY), and *Bharatiya Prakritik Krishi Paddhati* (BPKP). These programs have laid a foundational framework for agroecological transitions by focusing on policy support, certification mechanisms, and capacity-building initiatives. The pace of adoption needs to be accelerated. Achieving the target of bringing 25% of agricultural land under natural and chemical-free farming by 2070 will therefore require a combination of technological and institutional interventions, supported by implementation strategies tailored to agro-climatic suitability and local farming systems.

As explained in Annexure VI (Part-2), targeting should integrate agronomic (productivity, fertiliser use), biophysical (soil, rainfall, elevation), and socio-economic (community institutions like SHGs) parameters to secure long-term nutrition and environmental sustainability. Natural Farming can be applied both to rainfed areas (boosting yields, profitability, and nutrition) and Green Revolution hotspots addressing water stress and soil degradation.

c) **Enhancement of aggregate livestock productivity:** Requires converging production and demand-side strategies across milk, feed, and fodder value chains, to ensure food security, climate resilience, and reduced emissions intensity. State-wise bovine breed analysis, feed needs, and fodder shortage mapping will help to boost output while optimising land use. To balance the trade-off, there is a need for:

   i. **Breed improvement:** Breed improvements may be facilitated through technological interventions, such as artificial insemination and in-vitro fertilisation, guided by agro-climatic and socio-economic suitability of the breeds.

   ii. **Improve animal nutrition and health:** Breed improvements impact feed and fodder demand that could constrain fodder availability in India. As a result, it is imperative to assess the future feed requirements of different breeds. Developing institutional mechanisms for channeling fodder from surplus to deficit states can address spatial imbalances. To overcome temporal shortages, particularly in green fodder, practices such as silage-making should be promoted in fodder-surplus regions. The improvement in animal nutrition would potentially also improve animal health and productivity.

iii. **Feed efficiency:** Improve overall feed quality with high-protein options to boost livestock productivity, thereby reducing land pressure as enhanced efficiency lowers total fodder demand.

The increase in livestock productivity would require a dedicated focus on animal nutrition and adequate availability of fodder, increasing the pressure on land. This will potentially necessitate an increase in India's cropping intensity even more.

2. **Adopt an integrated "agri-food" systems approach:** India's agricultural transition requires coordinated policy action across land, energy, and water systems; isolated interventions, such as solar irrigation without groundwater governance, electrification without subsidy reform, or renewable deployment without land-use planning, risk inefficiencies, fiscal stress, and competition with food production. Our analysis indicates that no single intervention can independently deliver meaningful mitigation or energy-efficiency co-benefits by 2070; whether focused on crop diversification, natural and chemical-free farming, or yield intensification, interventions scaled in isolation risk unintended trade-offs, as illustrated by the Green Revolution, which addressed food security but undermined long-term soil health and ecosystem resilience (John and Babu, 2021). Achieving durable outcomes, therefore, requires an agri-food systems approach that aligns production systems, dietary patterns, value chains, and environmental objectives across land, energy, food, health, biodiversity, and water systems (FAO, 2024). Initiatives such as the Pradhan Mantri Dhan-Dhaanya Krishi Yojana (PMDDKY) demonstrate the potential of such integration by converging crop diversification, rural livelihoods, and access to credit across 100 low-productivity districts. Scaling similar efforts through a whole-of-government approach-ensuring alignment across the Ministries of Agriculture, Energy, Water, and Health-can embed clean energy, micro-irrigation, electric farm machinery, healthy diets, and dual-use solutions such as agrivoltaics (Gómez-Casanovas et al., 2023) directly within agricultural development strategies.

3. **Conduct integrated assessment of the agri-food system for long-term planning and ambition setting:** Conduct integrated assessment of the agri-food system for long-term planning and ambition setting: To scale integrated interventions effectively, ambition setting must be future-sensitive, underpinned by robust scenario analyses and periodic reviews for adaptive governance, while accounting for socio-economic and climatic uncertainties. Maximising mitigation co-benefits from the agriculture sector by 2070 while balancing economic development requires a fundamental shift away from siloed, short-term planning approaches. Integrated Assessment Modelling (IAM) is essential for generating data-driven insights that support decision-making and navigate the complex interdependencies of climate, agriculture, and socio-economic systems (IPCC, 2014). For example, Jha et al. (2022) highlight that dietary shifts towards healthy diets could reduce India's emissions by ~60 % compare to baseline. Similarly, a robust IAM assessment, calibrated to India's national context, can integrate supply-side interventions with demand-side dynamics (e.g., rising incomes, urban dietary shifts), while quantifying trade-offs such as land-use competition between food security, afforestation goals and goals of other land requiring economic sectors.

Critically, it can assess how macroeconomic levers impact farm profitability and rural livelihoods, ensuring no population is marginalised in the transition. By embedding climate projections (e.g., monsoon variability, heat stress). This could be vital to align India's dual goals of becoming a Viksit Bharat by 2047 and a net-zero economy by 2070, while ensuring food systems transformation strengthens, rather than strains, the livelihoods of those who feed the nation.

4. **Implement an "Efficiency-first + clean energy solutions" strategy to achieve maximum efficiency within the sector:** The agricultural energy transition, driven primarily by irrigation demand, must follow an adaptation-first, agriculture-led sequencing to avoid energy-intensive lock-ins. Energy demand projections (Figure 3.17) indicate that simply substituting diesel and grid-connected pumps with solar pumps lowers emissions but does not curb total energy demand, as irrigation volumes and groundwater dependence continue to rise. An efficiency-first strategy is therefore essential, prioritising resource-efficient practices such as micro-irrigation, precision and daytime irrigation scheduling, sustainable practices, and rationalised input usage to reduce both water and energy intensity while strengthening climate resilience. Evidence from Box 3, demonstrates that solarisation, when explicitly linked to efficient water use, can induce behavioural change and deliver up to 30% reductions in water and energy consumption.

   Building on these efficiency and adaptation gains, clean energy interventions, including renewable adoption, electrification of farm operations, and the use of clean fuels such as Compressed Biogas (CBG), can then be scaled to decouple productivity growth from energy use. Mechanisation, which is inevitable by mid-century, need not lock in emissions if the transition is directed towards electric and clean-fuel-based machinery, as reflected in the net-zero pathway. Custom Hiring Centres (CHCs) will be central to this transition, lowering upfront costs, improving the utilisation of clean machinery, and extending access to smallholders who cultivate farms averaging less than 1.1 hectares, thereby ensuring that mechanisation delivers productivity, energy-efficiency, and mitigation co-benefits in a resource- and fiscally sustainable manner.

ANNEXURES

Annexure I: Country-Specific Emission Factors for the Study

Table Annex. I.1: Country-specific emission factors for Rice cultivation

Region/Ecosystem	Water Regime	Emission Factor (kg CH_4/ha)
Irrigated	Continuously Flooded	159.74
	Single Aeration	66.2
	Multiple Aeration	19.3
Rainfed	Drought Prone	68.84
	Flood Prone	189
Deep Water	Deep Water	190

Source: *MoEFCC, 2018 (BUR 4 emission factors are unavailable)*

Table Annex. I.2: Agriculture soil emissions: Emission factors

Parameter	Country-specific emission coefficients/ factors (% of N converted to N2O)
EF1 (N_2O emission from applied fertiliser)	0.55
EF4 (N_2O emission from volatilized N from fertiliser and manure)	0.50
EF5 (N_2O emission from leached and run-off N from fertiliser and manure)	0.50
FracGASF (Gas loss through volatilisation from inorganic fertiliser)	20
FracGASF-AM (Gas loss through volatilisation from manure)	20
Fracleach (Leaching loss of N from applied fertiliser and manure)	10

Source: *MoEFCC, 2023*

Table Annex. I.3: AWB: Emission factors (CH_4 and N_2O)

GHG Gas type	Emission Factor (kg GHG/kg biomass burnt)
CH_4	0.0027
N_2O	0.00007

Source: *BUR 2, 2019*

Table Annex. I.4: Livestock: Emission factors (CH_4 and N_2O)

Category	Sub-Category	Age Group	Methane Emission Factor		Nitrous Oxide
			Enteric Fermentation (kg CH_4/ head/ year)	Manure Management (kg CH_4/ head/ year)	Manure Management (kg N_2O/head/ year)
Indigenous Cattle	Dairy Cattle	Indigenous	28	3.5	0.0006
	Non-Dairy Cattle (indigenous)	0–1 year	9	1.2	0.0004
		1–3 years	23	2.8	0.0004
		Adult	32	2.9	0.0004
Crossbred Cattle	Dairy Cattle	Cross-bred	43	3.8	0.0006
	Non-Dairy Cattle (cross-bred)	0–1 year	11	1.1	0.0004
		1–3 years	26	2.3	0.0004
		Adult	33	2.5	0.0004
Buffalo	Dairy Buffalo		50	4.4	0.0006
	Non-Dairy Buffalo	0–1 year	8	1.8	0.0004
		1–3 years	22	3.4	0.0004
		Adult	44	4	0.0004

Source: *MoEFCC, 2004*

Annexure II: Policy Typologies

Table Annex. II.1: Policy mapping and assumptions behind scenarios

Scenarios	Assumptions
Cropping intensity	*Pradhan Mantri Krishi Sinchayee Yojana–Micro Irrigation* (PMKSY-MI) and the *Accelerated Irrigation Benefits Programme* (AIBP) are expected to enhance cropping intensity, though overall increase may be limited by small landholdings and gradual labour shift away from agriculture.
Crop diversification	Policies like the *Crop Diversification Programme* (CDP) and *Mera Paani Meri Virasat* (MPMV) aim to reduce reliance on rice, wheat, and sugarcane. Coupled with rising income and demand for pulses, millets, and horticulture, these shifts are likely to make alternative crops more profitable and widely adopted.
Yield intensification	Schemes like *Sub-Mission on Agricultural Mechanisation* (SMAM) and Custom Hiring Centres (CHCs) aim to improve access to farm machinery and enhance cultivation efficiency. Further, *Soil Health Card* (SHC) and *Integrated Nutrient Management* (INM) initiatives aim to improve soil fertility and support sustainable yield growth.
Natural and Chemical-free farming	Schemes like National Mission on Natural Farming, *Paramparagat Krishi Vikas Yojana* (PKVY), and *Bharatiya Prakritik Krishi Paddhati* (BPKP) aim to promote natural and organic farming through targeted support and awareness. Further *Participatory Guarantee Scheme* (PGS) and *National Programme on Organic Production* (NPOP) certifications encourage adoption by offering credible certification systems for organic produce.
Fertiliser uptake efficiency	Fertiliser uptake is expected to improve through interventions like neem-coated urea, fertigation, micro irrigation, and *Integrated Nutrient Management* (INM). Support measures such as gypsum distribution under the National Mission for Sustainable Agriculture and upcoming technologies like AI-driven precision agriculture further enhance nutrient efficiency and application.
Conventional rice cultivation practices	Policies like the *National Food Security Mission* (NFSM) and *Bringing Green Revolution to Eastern India* (BGREI) promote practices such as System of Rice Intensification (SRI) and Direct Seeded Rice (DSR), which help reduce methane emissions from rice cultivation.
Crop residue burning	Government initiatives such as crop residue management schemes and the promotion of equipment like Happy Seeders aim to reduce Agricultural Waste Burning (AWB).
Bovine productivity	An overall increase in livestock productivity is assumed, driven by government initiatives focused on animal health and nutrition. Programs such as the *National Dairy Plan* (NDP), which promotes ration balancing, and state-wise fodder development efforts led by institutions like Indian Grassland and Fodder Research Institute (IGFRI), are expected to enhance per-animal yield (kg/day).

Development of Current Policy Scenario and Net Zero Scenario

Long-term strategic pathways were developed through iterative, multi- stakeholder consultations (with 30+ experts). The process evaluated adoption trajectories of different interventions, and impact potential is quantified across temporal horizons (2020–2070). The four-phased pathways development process comprised:

1. **Policy identification:** Mapping government policies shaping agricultural production systems.
2. **Policy typology development:** Classification of policies into typologies based on their primary outcome (productivity enhancement, sustainable agriculture practices, agricultural intensification, etc.) with their corresponding mitigation co-benefits.
3. **Scenario definition:** Identifying key variables against the policy typologies.
4. **Scenario Building:** Consultations for consensus building with stakeholders, experts and Working Group members to align on differentiated assumptions for scenarios across near-term (2030), mid-century (2047), and long-term (2070) horizons.

The last step is followed for the development of two pathways: **Current Policy Scenario (CPS) and Net Zero Scenario (NZS)**.

Annexure III: Emissions in Sustainable Rice Systems

Table Annex. III.1: Alternative Rice cultivation strategies and their emission reduction potentials

State	Alternative Cultivation Strategy	Emission Reduction Potential from Literature (%)	References
Assam	Semi-Dry Cultivation	29.0	(Gorh and Baruah 2019)
			(Gogoi, Baruah, and Gupta 2008)
Andhra Pradesh (excluded)	SRI + AWD	26.8	(Duvvuru and Motkuri 2013)
Bihar	DSR +AWD	89.7	(Pathak and Aggarwal 2012)
	SRI +AWD	71.5	
	AWD	29.5	
	DI	100	
Haryana	DSR + AWD	89.5	(Pathak and Aggarwal 2012)
	SRI +AWD	64.0	
	AWD	29.1	
	DI	100	
Odisha	AWD	75.0	(Mohanty et al. 2017)
Punjab	DSR +AWD	89.5	(Pathak and Aggarwal 2012)
	DSR	82.0	
	SRI + AWD	64.0	
	DI	100	
Tamil Nadu	AWD	52.8	(Thanakkan and Selvaraj 2020)
	DSR + AWD	16.6	(Thanakkan and Selvaraj 2020)
	SRI + AWD	26.8	(Thanakkan and Selvaraj 2020)
	DI	68.0	(Thanakkan and Selvaraj 2020)
			(Parthasarathi et al. 2019)
Telangana	SRI + AWD	23.4	(Nirmala et al. 2021)

State	Alternative Cultivation Strategy	Emission Reduction Potential from Literature (%)	References
Uttar Pradesh	DSR + AWD	89.5	(Pathak and Aggarwal 2012)
	SRI + AWD	64.0	
	AWD	29.1	
	DI	100	
West Bengal	DSR + AWD	89.7	(Pathak and Aggarwal 2012)
	SRI + AWD	71.5	
	AWD	29.5	
	DI	100	

Note: ***DSR*** *- Direct Seeded Rice*
SRI *- System of Rice Intensification;*
AWD *- Alternate Wetting and Drying;*
DI: *Drip Irrigation*

Annexure IV: Energy Demand Projections of Irrigation Pumping

Steps in Figure 2.1 are explained below:

1. **Crop demand projections:** Demand projections for this study are drawn from NITI Aayog's Working Group Report on Crop Husbandry, Agricultural Inputs, and Demand–Supply, which provides estimates up to 2047. These projections were subsequently extended to 2070 in collaboration with the scientists and experts from Indian Council of Agricultural Research (ICAR) The crops considered are rice, wheat, maize, pulses, oilseeds, sugarcane, and cotton. Together, these account for the majority of India's irrigated land and water consumption.
2. **Water demand estimation:** The water demand for pumping is estimated from crop production requirements. Crop production (in million tonnes) is translated into crop area using projected yields, with a distinction drawn between rainfed and irrigated shares using crop specific irrigation intensities. The table below (Table Annex. IV.1) presents the share of each major crop's area that was irrigated in 2020.

Table Annex. IV.1: Crop-wise share of irrigation as in 2020- Baseline

Crop	Irrigated Share (2020)
Rice	60.9%
Wheat	94.6%
Maize	36.7%
Arhar (pigeonpea)	4.2%
Gram (chickpea)	42.8%
Groundnut	29.1%
Rapeseed & Mustard	79.9%
Sugarcane	96.0%
Cotton	35.7%

Multiplying each crop's irrigated share by its water productivity coefficient (kg crop per m^3) yields the total volume of irrigation water demand (Sharma et al, 2018).

Not all irrigation water is lifted by pumps – a portion is supplied by gravity flow in canal command areas and by tank irrigation. A pumping share factor is applied to reflect the fraction of irrigation water that requires energy for pumping. Currently, about 60–70% of India's irrigated area is served by groundwater (wells and tube wells) or other lift systems, which implies that roughly two-thirds of irrigation water is pumped (The remainder from canals may involve minor lifting at field level, but is largely gravity-fed). A baseline value of 75% is used as the share of irrigation water that is pumped (MoAFW, 2022). For future scenarios, this factor can change based on investments in canal infrastructure or micro-irrigation (for instance, expanded surface irrigation could reduce reliance on pumps, whereas deeper groundwater use could increase energy needed per unit water).

Energy demand estimations: Energy demand for irrigation is calculated by converting pump-dependent water requirement into useful energy and then into final energy, accounting for operating conditions and technology parameters.

1. **Pump discharge and utilisation:** Based on the 5th Minor Irrigation Census (MIC) in 2017 (MoJS, 2024) and supporting field studies, an average irrigation pump is considered to be rated as 5–6 Horsepower (HP), with a discharge rate of 20 m^3/h under a nominal head of 25 metres. Utilisation differs sharply by technology: electric and solar pumps operate for 750 hours annually, while diesel pumps operate for 250 hours due to higher fuel costs. Using these assumptions, the model reproduces a base-year pump stock of 20 million electric and 10 million diesel units, consistent with estimates in MIC 2017.
2. **Dynamic head:** The average pumping head in 2019 was 28 m, and is a representative value across shallow and deep groundwater systems reported in MIC 2017 (MoJS, 2024). This is projected to rise to 50 m by 2070 as groundwater tables decline.
3. **Pump efficiency:** Overall pump–motor efficiency is assumed to be 30% for diesel and 36% for electric pumps in 2020, improving gradually to 45–55% by 2070 with technology advances and better maintenance (EMC, 2018). Solar pumps use high-efficiency electric motors and are assumed to perform comparably to grid-electric pumps.
4. **Energy calculation:** Useful energy required for pumping is estimated as:

$$\textbf{Useful Energy Demand} = E_u = N_p \times H_p \times A_h$$

Where,

$$N_p = \text{Number of active pumps} = \frac{\text{Ground Water Demand}}{\text{Average Discharge Rate} * \text{Functioning Hours per Year}}$$

H_p = Horsepower of lifting device, assumed to be 5 based on MIC 2017.

A_h = Annual Hours Usage, assumption based on MIC, IWMI, and consultations.

$$\text{Final Energy Demand } E_f = \frac{EU}{n}$$, where η is overall efficiency of the pump

Modelled outputs are validated against observed consumption: 207 TWh of electricity in agriculture in 2019-20 (CEA 2024) and about 6-8 MMT of diesel annually (Petroleum Planning and Analysis Cell (PPAC)). The base-year estimates are within a narrow margin of these reported values, confirming the robustness of the approach.

Annexure V: Energy Demand Projections of Land Preparation

Steps in Figure 2.3 are explained below:

1. **Mechanised land preparation area:** The starting point is the gross cropped area (GCA) as per the cropping intensity scenario for Current Policy Scenario in Table 2.4. The extent of mechanisation determines what share of this area is prepared using machines rather than manual or animal power. The current level of mechanisation in India is 47%. For the base year 2019, this translates to 93 Mha prepared by tractors or tillers.
2. **Methods of land preparation:** Mechanised land preparation in India is dominated by tractors, but power tillers also play a critical role, especially in smallholder farms. While tractors are known to form the majority of farm power in absolute numbers, exact and recent data on the shares of tractors and tillers in mechanised farming has not been consistently documented. That said, the share of mechanical and electrical power in farm power has risen markedly from just 7% in 1960–61 to over 87% in 2009–10, replacing animate power sources like animals and humans (Tiwari et al, 2019). Mechanisation trends suggest that tractors dominate field-level tillage, yet power tillers remain relevant for small, fragmented farms. Over 85% of Indian farmers are small or marginal holders (owning under 2 hectares of land), making full-sized tractors expensive or logistically cumbersome. Power tillers are more cost- efficient, manoeuvrable, and versatile for such small plots, particularly in paddy and horticultural systems (Rath et al, 2024).

Given the lack of recent national data on the share of tractors and tillers, this module retains the conservative assumption that for every two power tillers there is one tractor in terms of land coverage capacity (the hours required to prepare an equivalent area of land), a conversion metric commonly used in established technical analyses.

Estimating energy demand: The energy requirement for land preparation is estimated by first determining the work effort—measured as operating hours per hectare, and the corresponding

fuel consumption rate of each implement type. Literature and field studies provide benchmarks for both hours per hectare and energy per hour, with tractors generally requiring fewer hours per hectare but consuming more fuel per hour, and power tillers requiring longer operating times at lower hourly fuel rates (20 hours compared to 8 hours). However, energy intensity per hectare is not fixed, it can vary substantially depending on soil type, moisture conditions, implement depth, and operator skill, which influence the number of passes required and the effective load on the engine. These variations highlight the need for more detailed, crop- and region-specific studies to capture the true range of energy use across India's diverse farming systems.

On the basis of these assumptions, energy intensity per-hectare is obtained for tractors and tillers. These figures are then applied to their respective areas. The results are aggregated to arrive at total energy demand for land preparation.

$$E = GCA * Mechanisation\ (\%) * \sum_{v} (A_{*} I_{v})$$

Where, A is the area prepared by implement type, I is the energy intensity per hectare, GCA is the Gross Cropped Area.

This formulation captures both differences in implement efficiency and variations in operating practices. In the base year, applying these intensities to the mechanized area yields diesel use consistent with national estimates of agricultural fuel consumption. This methodology is limited to tractors and power tillers for estimating energy demand. It does not explicitly account for other forms of mechanisation such as laser land levellers, seed drills, or the emerging role of drones and automated machinery in land preparation and field management.

Annexure VI: Scenario Rationale

1. Strategic opportunities for diversifying areas away from rice to nutri-cereals in India

Classifying states: Potential for diversification & Potential for rice expansion

The following figure presents an analytical classification of Indian states based on their current and decadal trends of area, production, and yield (APY) of rice cultivation. To assess their potential for diversification away from rice, Indian states have been plotted based on two composite indicators on area and yield, respectively in Figure Annex VI.1.

How to read the graph:

1. X axis–Area composite score = rice area as (%) of the state's GCA + rice area growth rate (CAGR) from 2014 to 2023.
2. Y axis–Yield composite score = current rice yield in the states and yield CAGR from 2014 to 2023.
3. Size of the bubble: % of the State's contribution to India's total production.
4. Orange states: States where short-term diversification away from rice is feasible due to sufficient production of nutri-cereals. This means that public procurement channels in the states can replace rice with nutri-cereals without trade-offs.

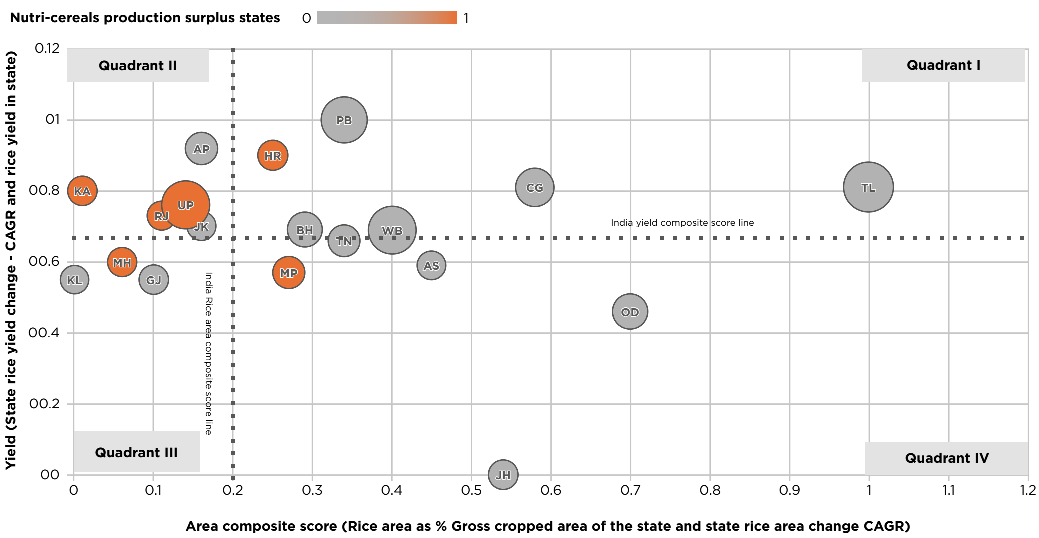

Figure Annex VI.1: State distribution map based on rice area and yield trends (Authors' analysis)

Quadrant I: Taking into account both the current levels and growth rates of rice area and yield, states like Punjab, Haryana, and Telangana exhibit potential for natural diversification away from rice in the future. Long-term sustainability of rice production remains a concern for these states, as biophysical constraints such as groundwater depletion and soil health degradation are likely to create pressure. Some diversification away from rice in these states is expected to occur gradually, driven more by ecological necessity than immediate economic incentives.

Quadrant II: States in these quadrants show varied potentials for diversification and rice area expansion. The trajectory of diversification in states like Andhra Pradesh and Jammu and Kashmir is defined by declining trends in area under rice cultivation, suggesting natural diversification is occurring. In contrast, states like Uttar Pradesh, Rajasthan, and Karnataka show positive trends in rice expansion with smaller area under cultivation and higher yields. These states, unlike the previous two states, remain at risk of future rice expansion, particularly if irrigation access improves.

Quadrant III: These states currently have low rice cultivation area and yield, but are experiencing positive growth rates in both, indicating a potential risk of future rice expansion. Kerala is the only exception, showing a negative growth rate in both area and yield.

Quadrant IV: This group includes states where yields remain low and rice area expansion exhibits varying trends. These states present a strong case for diversifying some areas away from rice. Diversification would offer considerable economic and resilience benefits by shifting to crops better suited to local conditions. This approach aligns with the primary objectives and outcomes intended under the recently announced PM Dhan Dhanya Krish Yojana (PIB, 2025 (a)).

While states have been identified for diversification away from rice, it is essential to adopt a phased approach that accounts for the value chain readiness of alternative crops. In the following suggestive roadmap in Figure Annex VI.2, we focus on diversification to nutri-cereals, which received strong support from the GoI in recent years.

Suggestive Roadmap: Supporting Diversification through procurement by Food Welfare Programmes

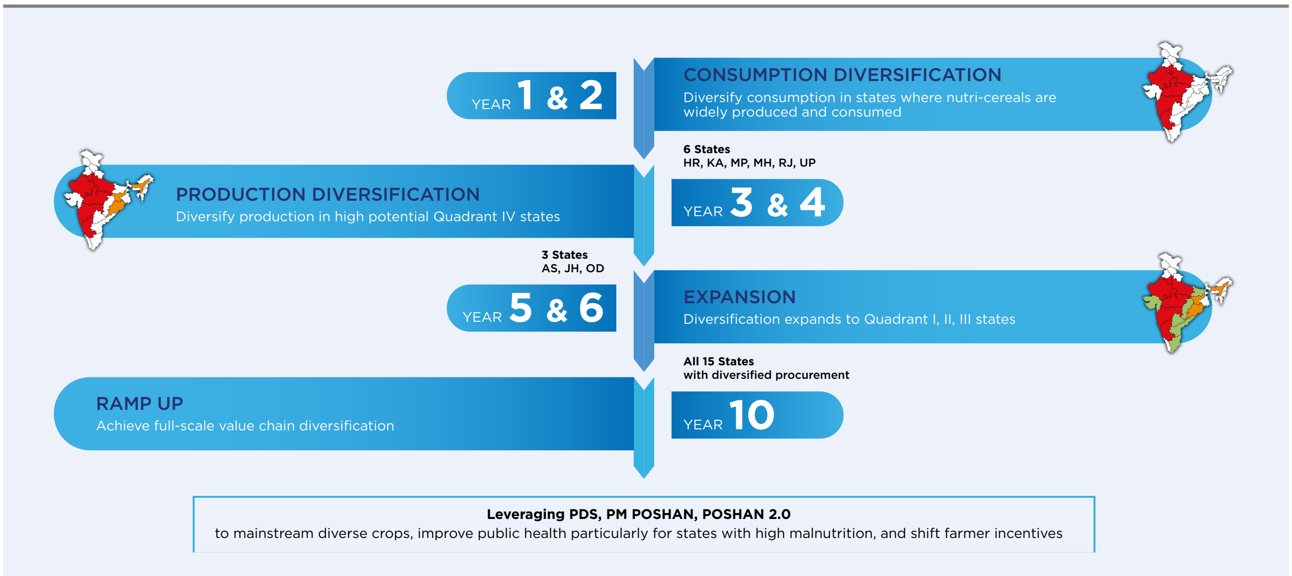

Figure Annex VI.2: Crop diversification opportunities from rice to nutri-cereals for India

2. Natural farming: A Scalable Agroecological Pathway for India

Natural farming (NF) presents a promising alternative to input-intensive agriculture, particularly in ecologically fragile and economically vulnerable regions. To scale NF in a way that unlocks its potential to enhance incomes and resilience of farms while ensuring nutrition security, a phased approach with strategic focus on specific geographies and communities and leveraging existing institutional and social capital is essential.

Scaling Natural Farming in rainfed areas for more equitable and sustainable agricultural growth:

Rainfed agriculture covers 51% of India's Net Sown Area (NSA) contributes 40% of food production, and is characterised by low productivity, low input use, and monsoon-dependent yield volatility (MoAFW, 2024). These rainfed areas face acute climate risks while supporting 81% of the rural poor, including marginal, tribal, and smallholder farmers (Gopinath et al., 2013). Natural Farming (NF) offers a low-risk, high-reward opportunity for these regions. Transitioning to Natural Farming (NF) can enhance productivity and help raise farmers' yields and profitability. Since a significant proportion of these farmers consume their produce, Natural Farming (NF) would also appeal to them given its focus on practices that promote health and nutrition, such as crop diversification (Annex VI.3). It would also help bring stability and resilience to *rainfed* farm systems by fostering soil health and practices that focus on climate resilience. The National Mission on Natural Farming (NMNF) also prioritises rainfed regions for Natural Farming (NF) scale-up.

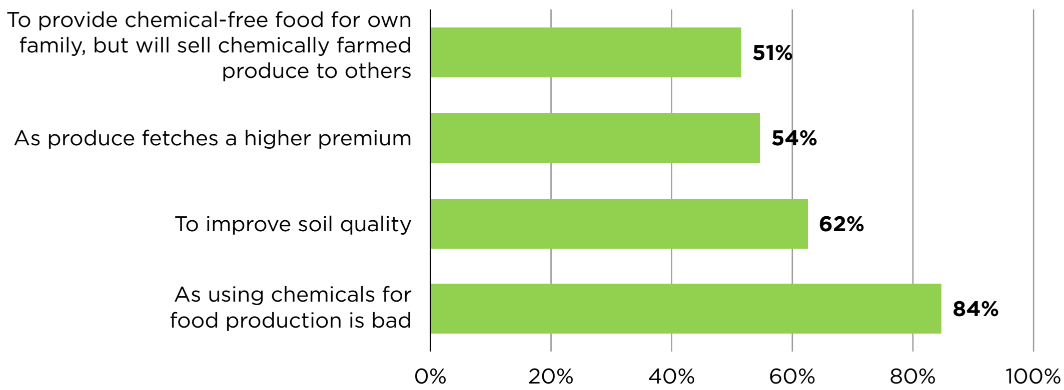

Figure AnnexVI.3: Motivations of farmers to adopt Natural Farming

Source: *Issue Brief - "What drives Natural Farming adoption in India?" Evidence from Farmer Behaviour and Practise Trends, CEEW (to be published)*

Green revolution regions may also hold opportunity hotspots for natural farming, based on targeted evidence:

India's Green Revolution (GR) regions, like Punjab, are now grappling with deep-rooted ecological imbalances. Years of intensive input use, incentivised by input subsidies, have led to declining soil fertility, falling groundwater tables, and public health concerns linked to excessive pesticide use. In this context, Natural Farming (NF) offers an opportunity for ecological restoration and enhancing long-term agricultural resilience. However, given that farmers in these regions are typically risk-averse and yield-focused, the regional hotspots with extreme ecological stress, putting farm productivity and incomes at high risk of decline, may only offer a window for Natural Farming (NF) adoption in the short term. Building compelling proofs of concept in Green Revolution regions with a focused strategy centred on evidence generation and localised demonstrations would expand the Natural Farming (NF) opportunity in Green Revolution regions towards the mid-term. Natural Farming (NF) programmes like *National Mission on Natural Farming* (NMNF) are also building on similar approaches, targeting the creation of Natural Farming (NF) clusters in Green Revolution regions with high input use and proximity to major rivers (MoAFW, 2024).

Field evidence from the APCNF programme suggests that APCNF GPs in traditional Green Revolution regions such as Godavari and Krishna are witnessing high uptake of natural biostimulants in portions of their land as they transition into chemical farming with farmers motivated by health and soil concerns as indicated in Annex VI.4 (Issue Brief - "What drives Natural Farming adoption in India?" Evidence from Farmer Behaviour and Practise Trends, CEEW (to be published)).

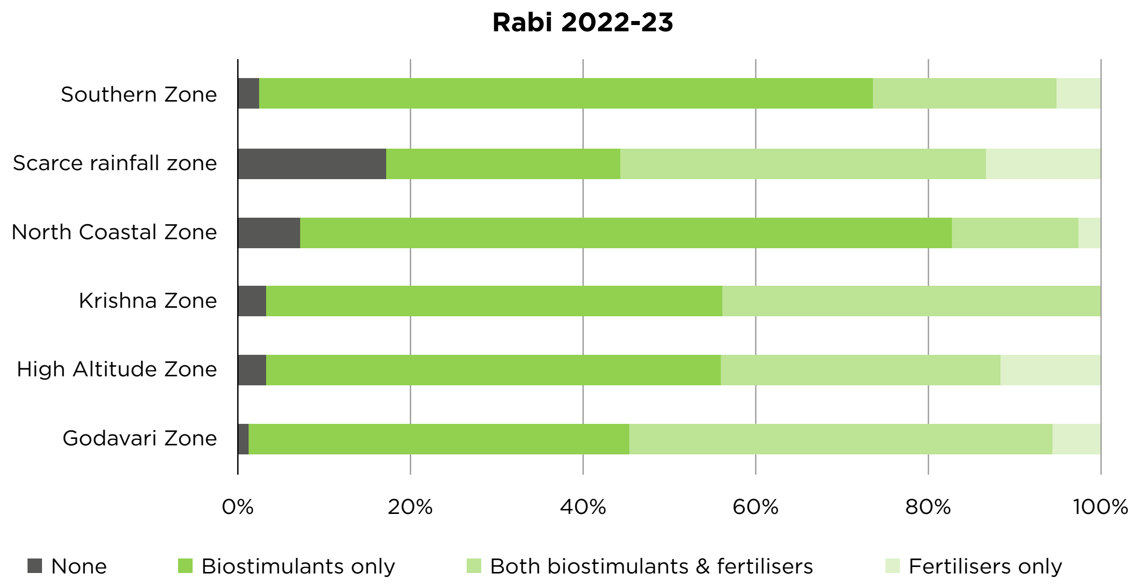

Figure AnnexVI.4: Biostimulant adoption in different agro-climatic zones in Andhra Pradesh

By promoting diverse, indigenous crops, NF supports prosumption (production consumed in-house) and better household diets. Aligning NF with nutrition-focused programmes like mid-day meals, PDS, and ICDS can amplify its adoption and impact on both public health and local food systems.

The deep reach of SHGS, CRPs, and FPOs across rural India can scale natural farming through trusted, community-rooted institutions.

Institutionalisation at the community level has emerged as a critical success factor for scaling sustainable agriculture programmes, with village-level championship models such as Community Resource Persons playing a particularly important role. (CEEW, 2023). The APCNF initiative exemplifies this approach, leveraging Community Resource Persons (CRPs) to scale Natural Farming to over one million farmers across 26 districts in Andhra Pradesh in just nine years. This demonstrates the potential for decentralised, community-driven models to mainstream natural farming. Importantly, the institutional infrastructure necessary for such initiatives already exists. India has over 8.3 million Self-Help Groups (SHGs), many integrated into state and *National Rural Livelihood Missions* (NRLM). Additionally, networks such as Krishi Sakhis and over 8,000 Farmer-Producer Organisations (FPOs) offer robust platforms for peer-led extension services (PIB, 2024).

Moreover, these grassroots institutions are particularly active in areas dominated by rainfed farming and smallholder agriculture, making these regions a clear opportunity hotspot for natural farming adoption. For instance, in Odisha, Mission Shakti's SHG network plays a significant role in districts such as Kandhamal and Rayagada, which face high agroecological vulnerability yet have a long-standing tradition of ecological farming. In Chhattisgarh's Bastar region, SHG federations and Krishi Sakhis are central to farmer engagement, supported by both state and non-state actors promoting natural farming as a low-cost, climate-resilient alternative. Decentralised extension systems anchored in CRPs, SHGs, and FPOs not only build trust and adapt the interventions to local realities but also reduce the transaction costs of last-mile delivery, making them highly effective in driving behavioural change and embedding sustainable practices across India's diverse agricultural landscapes.

REFERENCES

References

1. Agarwal, N., Apoorve, K., & Wal, A. (2023). How to design scalable and sustainable programmes: Framework for India's sustainable agriculture initiatives. Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/how-can-india-design-scalable-and-sustainable-programmes-for-sustainable-agriculture- initiatives.pdf
2. Agriculture Statistics. (2024). Agricultural statistics at a glance 2023. Government of India, Ministry of Agriculture & Farmers Welfare, Department of Agriculture & Farmers Welfare. https://desagri.gov.in/wp-content/uploads/2024/09/Agricultural- Statistics-at-a-Glance-2023.pdf
3. APCNF. (n.d.). APCNF – Towards farmer prosperity, better citizen health, climate resilience and cooling of the planet. https://apcnf.in/global/
4. Barman, A., Saha, P., Patel, S., & Bera, A. (2022). Crop diversification: An effective strategy for sustainable agriculture development. In V. S. Meena, M. Choudhary, R. P. Yadav, & S. K. Meena (Eds.), Sustainable crop production: Recent advances (pp. 1–17). IntechOpen. https://doi.org/10.5772/intechopen.102635
5. Bhuvaneshwari, S., Hettiarachchi, H., & Meegoda, J. N. (2019). Crop residue burning in India: Policy challenges and potential solutions. International Journal of Environmental Research and Public Health, 16(5). https://doi.org/10.3390/ ijerph16050832.
6. Birthal, P. S., Khan, M. T., Negi, D. S., & Agarwal, S. (2014). Impact of climate change on yields of major food crops in India: Implications for food security. Agricultural Economics Research Review, 27. https://doi.org/10.5958/0974-0279.2014.00019.6
7. Central Electricity Authority-CEA. (2024). All India electricity statistics: General review 2024 (containing data for the year 2022–23). Ministry of Power, Government of India. https://cea.nic.in/ general-review-report/?lang=en
8. Central Electricity Authority-CEA. (2025). Updated growth report 2025. https://cea.nic.in/wp-content/uploads/general/2025/Updated_GR_2025_merged_new.pdf
9. CEEW. (2021). Policy Study on Sustainable Agriculture. https://www.ceew.in/sites/ default/files/ceew-policy-study-on-sustainable-agriculture-india_0.pdf
10. CEEW–IWMI. (2023). Evaluating policy coherence in food, land, and water systems: Evidence from India. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Initiative on National Policies and Strategies. 124p. https://www.ceew.in/publications/evaluating-policy-coherence-in-food-land-and- water-systems-of-india
11. Chand, R. (2025). Reimagining agriculture for growth, poverty, nutrition, and sustainability. Journal of the International Association of Agricultural Economists, 1(March). https://doi.org/10.1111/agec.70015.

12. Chhabra, A., Manjunath, K. R., & Panigrahy, S. (2009). Assessing the role of Indian livestock in climate change. ISPRS Archives, XXXVIII-8/W3, 359–364. https:// www.researchgate.net/ publication/271702897
13. Chuphal, D. S., Kushwaha, A. P., Aadhar, S., & Mishra, V. (2024). Drought atlas of India, 1901–2020. Scientific Data, 11(1), 7. https://doi.org/10.1038/s41597-023- 02856-y
14. DAHD. (2005). 17th Indian Livestock Census: All-India Summary Report. Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. https://dahd.gov. in/sites/ default/files/2025-05/17thIndianLivestockCensusAll-IndiaSummaryReport. pdf
15. DAHD. (2007). 18th Livestock Census: All India Report. Ministry of Agriculture and Farmers Welfare, Government of India. https://iss.icar.gov.in/Livestock_ Documents/18th_Livestock_ Census.pdf.
16. DAHD. (2018). Basic Animal Husbandry and Fisheries Statistics 2018. Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. https://iss.icar.gov. in/.
17. DADH. (2019). 20th Livestock Census: All India Report. Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. https://ruralindiaonline.org/ en/library/ resource/20th-livestock-census-2019-all-india-report/.
18. DAHD. (2023). Basic Animal Husbandry Statistics 2023. Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. https://dahd.gov.in/sites/ default/files/2024-10/ BasicAnimalHusbandryStatistics2023.pdf.
19. Das, P., Singh, V., Stevanović, M., Kumar Jha, C., Bodirsky, B. L., Beier, F., Humpenöder, F., Leip, D., Chen, D. M. C., Crawford, M., von Jeetzen, P., Molina Bacca, E., Soergel, B., Springmann, M., Dietrich, J. P., Popp, A., Kumar Gosh, R., & Lotze-Campen, H. (2023). A healthy, sustainable, and inclusive food system transformation for India. https://foodsystemeconomics.org/wp-content/uploads/Das-et-al.-2023.pdf
20. Dhruw, U. K., Roy, D. K., & Verma, P. D. (2024). India's growth in agricultural mechanisation during last decades. International Journal of Advanced Biochemistry Research, 8(3 Suppl C), 178–181. https://doi.org/10.33545/26174693.2024. v8.i3Sc.715
21. EMC. (2018). Study of agriculture pump sets in the State of Kerala: Detailed project report. Energy Management Centre–Kerala https://keralaenergy.gov.in/files/Energy_ Efficiency_ study_of_Agriculture_Pump_sets.pdf
22. FAO. (2021). The state of the world's land and water resources for food and agriculture – Systems at breaking point: Synthesis report 2021. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb7654en
23. FAO. (2024) Food Balance Sheets. Retrieved April 24, 2025. https://www.fao.org/ faostat/ en/#data/FBS.
24. FAO. (2025). Glossary. Retrieved April 24, 2025. https://openknowledge.fao.org/ server/ api/core/bitstreams/317db554-c763-4654-a0d3-24a8488bbc3a/content/status-women-agrifood-systems-2023/glossary.html
25. Fertiliser Association of India (FAI). (2024). Annual Review of Fertiliser Production and Consumption 2023–24. https://www.faidelhi.org/member/AR-Full-Rep.pdf.
26. Gogoi, N., Baruah, K. K., & Gupta, P. K. (2008). Selection of rice genotypes for lower methane emission. Agronomy for Sustainable Development, 28(2), 181–186. https://doi. org/10.1051/agro:2007052

27. Gómez-Casanovas, N., Mwebaze, P., Khanna, M., Branham, B., Time, A., DeLucia, E. H., Bernacchi, C. J., Knapp, A. K., Hoque, M. J., Du, X., Blanc-Betés, E., Barron- Gafford, G. A., Peng, B., Guan, K., Macknick, J., Miao, R., & Miljkovic, N. (2023). Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production. Cell Reports Physical Science, 4(8), Article 101518. https:// doi.org/10.1016/j.xcrp.2023.101518
28. Gopinath, K. A., Dixit, S., Chary, G. R., Srinivasarao, Ch., Osman, M., Raju, B. M. K., Ramana, D. B. V., Venkatesh, G., Grover, M., Maheswari, M., & Venkateswarlu,B. (2013). Improving the rainfed farming systems of small and marginal farmers in Anantapur and Adilabad districts of Andhra Pradesh. Central Research Institute for Dryland Agriculture, Hyderabad, Andhra Pradesh. https://www.researchgate.net/ publication/259659509_Improving_the_Rainfed_Farming_Systems_of_Small_and_Marginal_Farmers_in_Anantapur_and_Adilabad_Districts_of_Andhra_Pradesh
29. Gorh, D., & Baruah, K. K. (2019). Estimation of methane and nitrous oxide emission from wetland rice paddies with reference to global warming potential. Environmental Science and Pollution Research, 26(12), 11522–11532. https://doi.org/10.1007/ s11356-019-05026-z
30. Government of India, Ministry of Rural Development. (n.d.). SHG count. https:// nrlm.gov.in/shgReport.do?methodName=showIntensiveStateWiseReport
31. Gupta, N., Pradhan, S., Jain, A., & Patel, N. (2021). Sustainable agriculture in India 2021: What we know and how to scale up. Council on Energy, Environment and Water (CEEW). https://www.ceew.in/sites/default/files/CEEW-FOLU-Sustainable- Agriculture-in-India-2021-20Apr21.pdf
32. IPCC. (2006). 2006 IPCC guidelines for national greenhouse gas inventories: Volume 1: General guidance and reporting. Task Force on National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change. https://www.ipcc-nggip. iges.or.jp/public/2006gl/index.html
33. IPCC. (2019). "Interlinkages between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options." In 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. N.p.: Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/sites/4/2022/11/ SRCCL_Chapter_6.pdf?utm_source.
34. IPCC. (2014). The IPCC Fifth Assessment Report. https://www.ipcc.ch/site/assets/uploads/2018/04/ipcc_ar5_leaflet.pdf.
35. Indian Dairy Association. (2012). 19th Livestock Census – 2012: All India Report. https:// indiandairyassociation.org/pdf/info/19th-Livestock-Census-2012.pdf
36. Jha, C. K., Singh, V., Stevanović, M., Dietrich, J. P., Mosnier, A., Weindl, I., Popp, A., Schmidt-Traub, G., Ghosh, R. K., & Lotze-Campen, H. (2022). The role of food and land use systems in achieving India's sustainability targets. Environmental Research Letters, 17(7), 074022. https://doi.org/10.1088/1748-9326/ac788a
37. John, S., & Babu, S. (2021). Lessons from the aftermaths of the Green Revolution on food system sustainability in India. Frontiers in Sustainable Food Systems, 5, 644559. https://doi.org/10.3389/fsufs.2021.644559

38. Kumar, R., Kumar, S., Yashavanth, B. S., Meena, P. C., Indoria, A. K., Kundu, S., & Manjunath, M. (2020). *Adoption of natural farming and its effect on crop yield and farmers' livelihood in India* (ICAR-National Academy of Agricultural Research Management, Hyderabad, India). https://www.niti.gov.in/sites/default/files/2021-03/NaturalFarmingProjectReport-ICAR-NAARM.pdf
39. Lewis, W. A. (1954). Economic Development with Unlimited Supplies of Labour. University of Texas. https://la.utexas.edu/users/hcleaver/368/368lewistable.pdf.
40. Meghalaya State Organic and Natural farming Policy 2023. https://investmeghalaya. gov.in/resources/homePage/17/megeodb/policies/farming2023.pdf?utm
41. Mishra, G. K., & Tiwari, R. P. (2014). Infertility management protocols for dairy animals. Indian Dairyman. https://www.researchgate.net/profile/Girish-Mishra-5/publication/322124388_Infertility_Management_of_Dairy_Animals/links/5a463187a6fdcce1971a9c4d/Infertility-Management-of-Dairy-Animals.pdf
42. MoAFW. (2017). Doubling Farmers' Income Report. In Doubling Farmers' Income–Volume I March of Agriculture Since Independence and Growth Trends. Ministry of Agriculture and Farmers' Welfare. https://agriwelfare.gov.in/Documents/ DFIpercent20Volume%201.pdf.
43. MoAFW. (2021). All India Report on Input Survey 2016-17. Agriculture Census. https://agcensus.da.gov.in/document/is2016/air_is_16-17_210121-final_220221.pdf.
44. MoAFW. (2022). Agricultural statistics at a glance 2022. Directorate of Economics and Statistics, Department of Agriculture and Farmers Welfare, Government of India. https://desagri.gov.in/wp-content/uploads/2023/05/Agricultural-Statistics-at- a-Glance-2022.pdf
45. MoAFW. (2024). National Mission on Natural Farming (NMNF) Operational Guidelines.
46. https://agriwelfare.gov.in/Documents/HomeWhatsNew/GuidelineofNMNF_FinalApproved_27122024.pdf
47. MoAFW. (2024). Rainfed Farming System. Department of Agriculture and Farmers Welfare, Government of India. https://agriwelfare.gov.in/en/RainfedDiv
48. MoEFCC. (2004). India's Initial National Communication to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India. https://unfccc.int/resource/docs/natc/indnc1. pdf
49. MoEFCC. (2018). India: Second Biennial Update Report to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India. https://unfccc.int/sites/default/files/resource/ INDIA%20SECOND%20BUR%202018.pdf
50. MoEFCC. (2021). India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India. https://unfccc.int/sites/default/files/resource/ INDIA_%20BUR-3_20.02.2021_High.pdf
51. MoEFCC. (2022). India's Long-Term Low-Carbon Development Strategy. Ministry of Environment, Forest and Climate Change, Government of India. https://moef.gov. in/uploads/2022/11/Indias-LT-LEDS.pdf
52. MoEFCC. (2023). India: Third National Communication and Initial Adaptation Communication to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India. https:// unfccc.int/sites/default/files/resource/India-TNC-IAC.pdf

53. MoEFCC. (2024). India Fourth Biennial Update Report. United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/resource/ India%20 BUR-4.pdf.

54. MoF. (2024). Economic Survey of India 2023-24. Government of India. Ministry of Finance, Department of Economic Affairs. India Budget. https://www.indiabudget. gov.in/ economicsurvey/doc/eschapter/echap01.pdf.

55. MoF. (2025). Economic Survey of India 2024-25. Government of India. Ministry of Finance, Department of Economic Affairs. India Budget. https://www.indiabudget. gov.in/ economicsurvey/doc/echapter.pdf.

56. Mohanty, S., Swain, C. K., Sethi, S. K., Dalai, P. C., Bhattacharyya, P., Kumar, A., Tripathi, R., Shahid, M., Panda, B. B., Kumar, U., Lal, B., Gautam, P., Munda, S., & Nayak, A. K. (2017). Crop establishment and nitrogen management affect greenhouse gas emission and biological activity in tropical rice production. Ecological Engineering, 104, 80–98. https:// doi.org/10.1016/j.ecoleng.2017.03.014

57. MoJS. (2024). 5th Minor Irrigation Census (MIC). Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, Government of India. https:// mowr.nic.in/irrigationcensus/

58. MPI. (2017). New Zealand Agriculture: A Policy Perspective (Document No. 27282). Ministry for Primary Industries, Wellington, New Zealand. https://www.mpi.govt.nz/ dmsdocument/27282-New-Zealand-Agriculture

59. NAAS. (2013). Livestock Infertility and Its Management (Policy Paper No. 59). National Academy of Agricultural Sciences, New Delhi. https://naas.org.in/Policy%20 Papers/ policy%2059.pdf

60. Nirmala, B., Tuti, M. D., Kumar, R. M., Waris, A., Muthuraman, P., Parmar, B., & Singh, T. V. (2021). Integrated assessment of system of rice intensification vs. conventional method of transplanting for economic benefit, energy efficiency and lower global warming potential in India. Agroecology and Sustainable Food Systems, 45(4), 475–495. https://doi.org/10.10 80/21683565.2020.1868648

61. NITI Aayog. (2022). A New Paradigm for Indian Agriculture: From Agroindustry to Agroecology. Government of India. https://www.niti.gov.in/sites/default/files/2023-03/A-New-Paradigm-for-Indian-Agriculture-from-Agroindustry-to-Agroecology. pdf.

62. NITI Aayog. (2024). NITI Aayog Working Group Report on Crop Husbandry, Agricultural Inputs, Demand and Supply 2024. Retrieved January 30, 2025, from https://www.niti. gov.in/sites/default/files/2024-02/Working%20Group%20 Report%20on%20Demand%20 %26%20Supply%20Final_V9.pdf.

63. Odisha Government (Mission Shakti). (2022). Mission Shakti: A Silent Revolution [Coffee-table book]. Women & Child Development and Mission Shakti Department, Government of Odisha. https://missionshakti.odisha.gov.in/sites/default/ files/2022-03/Coffee-table-book. pdf

64. OECD. (2019). Enhancing Climate Change Mitigation through Agriculture. OECD Publishing, Paris. https://doi.org/10.1787/e9a79226-en

65. Parthasarathi, T., Vanitha, K., Mohandass, S., & Vered, E. (2019). Mitigation of methane gas emission in rice by drip irrigation. F1000Research. https://doi. org/10.12688/ f1000research.20945.1

66. 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. https://doi.org/10.16943/ptinsa/2015/v81i5/48333

67. Patange, O., Purohit, P., Avashia, V., Klimont, Z., & Garg, A. (2024). Mitigation of non-CO2 greenhouse gases from Indian agriculture sector. Environmental Research Letters, 9. https://doi.org/10.1088/1748-9326/ad4e4e

68. PIB. (2011). Foodgrain Production Reaches Record 241.6 Million Tonnes. Press Information Bureau. https://www.pib.gov.in/newsite/PrintRelease.aspx?relid=75978

69. PIB. (2019). 4th Advance Estimates of production of major crops for 2018-19. https://www.pib.gov.in/Pressreleaseshare.aspx?PRID=1582362

70. PIB. (2021). Productivity of Dairy Animals. Press Information Bureau. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1707187#:~:text=As%20per%20Integrated%20Sample%20Survey,(as%20per%20FAO%20Statistics).

71. PIB. (2022a). Milk Production in India: The Journey of India's Dairy Sector. N.p.: Press Information Bureau. https://pib.gov.in/FeaturesDeatils. aspx?NoteId=151137&reg=3&lang=1.

72. PIB. (2022b). Increased foodgrain production in India: Six-fold rise in foodgrain production since independence. Press Information Bureau, Government of India. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/jul/ doc202272874801.pdf

73. PIB. (2022c). Cabinet approves India's updated nationally determined contribution to be communicated to the United Nations Framework Convention on Climate Change. Press Information Bureau, Government of India. https://pib.gov.in/PressReleasePage.aspx?PRID=1847813

74. PIB. (2023). Press release. Government of India. https://pib.gov.in/PressReleseDetailm.aspx?PRID=1939473&reg=3&lang=1

75. PIB. (2024). 8,875 FPOs have been registered across the country. Press Information Bureau, Government of India. https://www.pib.gov.in/PressReleaseIframePage. aspx?PRID=2040845

76. PIB. (2025a). India submits its 4th Biennial Update Report to the United Nations Framework Convention on Climate Change. Press Information Bureau, Government of India. https://www.pib.gov.in/PressReleasePage.aspx?PRID=2089589

77. PIB. (2025b). India's renewable revolution: Building clean power, made in India [Factsheet No. 149232]. Press Information Bureau, Government of India. https:// www.pib.gov.in/FactsheetDetails.aspx?Id=149232

78. PMO. (2023). PM launches 'Viksit Bharat @2047: Voice of Youth'. Prime Minister's Office, Government of India. https://www.pmindia.gov.in/en/news_updates/pm- launches-viksit-bharat-2047-voice-of-youth/

79. Prabhu, S., & Chitale, V. (2024). Decoding India's changing monsoon patterns – A tehsil-level assessment. Council on Energy, Environment and Water. https://www. ceew.in/sites/default/files/decoding-how-climate-change-is-changing-monsoon- rainfall-patterns-in-india.pdf

80. Rajasthan Organic Farming Policy. (2017). Rajasthan organic farming policy 2017. Department of Agriculture, Government of Rajasthan. https://cuts-cart.org/pdf/ Rajasthan_Organic_farming_Policy-2017.pdf

81. Ramesh, T., & Selvaraj, R. (2020). Evaluation of rice cultivation systems for greenhouse gas emissions and productivity. Tamil Nadu Agricultural University. https://www. researchgate.

net/publication/342347798_Evaluation_of_rice_cultivation_systems_for_greenhouse_gases_emission_and_productivity

82. Rao, A. (2024). Farm mechanisation in India's agriculture sector: Challenges and opportunities. India Briefing. https://www.india-briefing.com/news/india-farm- mechanisation-sector-opportunities-challenges-31243.html
83. Rath, I., Pradhan, P. L., Dash, R. C., Mahapatra, M., Sahoo, P. K., Behera, D., Behera, A., & Kamendra. (2024). Mapping the dynamics of agriculture mechanisation: Present dynamics and future trajectories. International Journal of Agriculture Extension and Social Development, 7(3), 181–186. https://doi.org/10.33545/26180723.2024. v7.i3c.425
84. Reddy, D. N., & Motkuri, V. (2013). SRI cultivation in Andhra Pradesh: Achievements, problems and implications for GHGs and work (MPRA Paper No. 52115). National Institute of Rural Development (NIRD). https://mpra.ub.uni-muenchen.de/52115/
85. Richards, M., & Sander, B. O. (2014). Alternate wetting and drying in irrigated rice. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). https://www.researchgate.net/publication/306372935_Alternate_wetting_and_drying_in_irrigated_rice_Implementation_guidance_for_policymakers_and_ investors
86. Sharma, B., Gulati, A., Mohan, G., Manchanda, S., Ray, I., & Amarasinghe, U. (2018). Water productivity mapping of major Indian crops. National Bank for Agriculture and Rural Development (NABARD) & Indian Council for Research on International Economic Relations (ICRIER). https://www.nabard.org/auth/writereaddata/tender/1806181128Water%20Productivity%20Mapping%20of%20Major%20Indian%20Crops,%20Web%20Version%20(Low%20Resolution%20 PDF).pdf
87. Sharma, H. R. (2023). Patterns, sources and determinants of agricultural growth in India. Indian Journal of Agricultural Economics, 78(1). https://isaeindia.org/wp- content/uploads/2023/04/2-H-R-SHARMA-KEYNOTE-PAPER.pdf
88. Sharma, S., Das, P., Chaturvedi, C., & Malyan, A. (2024). Sustainable rice cultivation in India. Council on Energy, Environment and Water (CEEW).
89. Shukla, A. K., Behera, S. K., Chaudhari, S. K., & Singh, G. (2022). Fertiliser use in Indian agriculture and its impact on human health and environment. Indian Journal of Fertiliser, 18(3), 218–237
90. Singh, B. (2023). Nitrogen use efficiency in crop production in India: Trends, issues, and challenges. Agriculture Research, 12, 32–44. https://link.springer.com/ article/10.1007/s40003-022-00626-7
91. Singh, V., Rastogi, A., Nautiyal, N., & Negi, V. (2017). Livestock and climate change: The key actors and the sufferers of global warming. Indian Journal of Animal Sciences, 87(1), 11–20. https://doi.org/10.56093
92. Tiwari, P. S., Singh, K. K., Sahni, R. K., & Kumar, V. (2019). Farm mechanization – Trends and policy for its promotion in India. Indian Journal of Agricultural Sciences, 89(10), 1559–1565. https://doi.org/10.56093/ijas.v89i10.94575

सत्यमेव जयते

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