Souvenir

National Seminar on Innovations in Agrophysics for Green Agriculture

ICAR-IIWM, Bhubaneswar
22-24 January 2026

Organized by

The Indian Society of Agrophysics,
Division of Agricultural Physics, ICAR-IARI, New Delhi
and
ICAR- Indian Institute of Water Management,
Bhubaneswar

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Published in January 2026

Published by
Dr. Pragati Pramanik Maity
Secretary
The Indian Society of Agrophysics
Division of Agricultural Physics
ICAR-Indian Agricultural Research Institute
New Delhi - 110012

Printed at
Mr. Print, C-126, First floor,
Naraina Industrial Area, Phase- I,
Naraina, Delhi-110028

Dr. Suresh Kumar Chaudhari
Director General
THE FERTILISER ASSOCIATION OF INDIA

Message

I am happy to know that the National Seminar on ***Innovations in Agrophysics for Green Agriculture*** will be organised at ICAR-IIWM, Bhubaneswar, during 22-24 January 2026. New and effective technologies have emerged globally for efficient and sustainable uses of the natural resources in the recent past. The development of new crop varieties help improve the productivity and yield of the crops. Agrophysics has a great potential to further enhance productivity levels in changing climate. We should give simultaneous attention to the use of modern technologies for the management of natural resources.

The agricultural production system is a highly complex subject, which encompasses various disciplines of agricultural sciences. The Agricultural Physicists have played a pivotal role in developing appropriate technologies across the agro-climatic regions of India to increase productivity. I hope that the delegates attending this Seminar will discuss and interact on issues related to the use of simulation modelling, biophysical techniques, remote sensing, drone technology, machine learning, artificial intelligence etc. for the efficient use of natural resources and to come out with viable research and management strategies for providing food and nutritional security and employment to the masses.

I wish the Seminar all success in its endeavours.

(Suresh Kumar Chaudhari)
DG, FAI

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16.01.2026

Message

I am indeed happy to know that the National Seminar on "Innovations in Agrophysics for Green Agriculture" will be organised at ICAR-IIWM, Bhubaneswar, during 22-24 January 2026. Impressive achievements have been made worldwide in the judicious management of natural resources and in enhancing agricultural production. However, the burgeoning demographic pressures have posed a formidable challenge to policymakers, scientists, and all implementing agencies for providing livelihoods to the teeming millions. The advent of seeds and the subsequent Green Revolution would not have been as spectacular without the matching agrophysical practices developed over the years by dedicated agricultural scientists across different agro-environments. However, as the present-day intensive agriculture demands, more cautious and pragmatic approaches are required to ensure environmental safety and sustainable food production. Multi-pronged approaches involving various components of modern-day agriculture need to be developed to tackle second-generation problems related to soils, water, and the environment.

I firmly believe that Indian agriculture has the potential and flexibility to overcome such intimidating tasks with the help of sturdy and devoted agricultural researchers. In this regard, the theme of the National Seminar "Innovations in Agrophysics for Green Agriculture" at ICAR-IIWM, Bhubaneswar, is apt and timely. The discussions and deliberations during the Seminar, I hope, will be highly useful and help solve the problems associated with agriculture, livelihoods, and global environmental security.

I wish the Seminar a grand success.

(A.K. Nayak)

MESSAGE

I am happy that the National Seminar on "Innovations in Agrophysics for Green Agriculture" will be organised at ICAR-IIWM, Bhubaneswar, during 22-24 January 2026. The seminar will have a special focus on the use of agrophysical technologies for green agriculture and a sustainable environment. The development of new crop varieties undoubtedly helps improve the crop yield potential; however, agrophysics can play a crucial role in unlocking the untapped potential of agricultural systems. Simultaneously, we should give due emphasis to the use of modern technologies for the management of natural resources. I hope the seminar will show the way to formulate strategies to mitigate problems in sustainable agriculture and move towards green agriculture.

On this occasion, I extend my best wishes to the organisers and participants.

Alok Sikka
Country Representative – India & Bangladesh

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Souvenir message

I am pleased happy to learn that the Indian Society of Agrophysics is organizing a National Seminar on **"Innovations in Agrophysics for Green Agriculture"** during **22–24 January 2026** at **ICAR–IIWM, Bhubaneswar**. I have been carefully watching the significant agrophysics research carried out in Indian agriculture. The advent of wonder seeds and the subsequent Green Revolution would not have been as spectacular without the corresponding agrophysics research developed over the years by dedicated researchers across different agro-environments.

However, present-day intensive agriculture demands a more cautious and pragmatic approach to ensure environmental safety and sustainable food production. In this context, the use of agrophysics techniques such as drones, remote sensing, simulation modelling, artificial intelligence, and machine learning for the development of green agriculture is indeed an apt and relevant subject.

It is expected that the participants in the Seminar, drawn from different spheres of agricultural science, will share their expertise and experience to widen the horizons of knowledge in the proposed area. I congratulate the organizers for choosing the most appropriate theme for the Seminar. I am sure that the discussions and deliberations during the Seminar will be of great benefit to the scientific community in resolving problems associated with agriculture, livelihoods, and green agriculture.

I wish the Seminar a grand success.

(Ch. Srinivasa Rao)

भाकृअनुप-भारतीय जल प्रबंधन संस्थान

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Date : 14.01.2026

डॉ. अर्जमादत्त षड़ंगी, निदेशक

Dr. Arjamadutta Sarangi, Director

Message

It gives me immense pleasure to note that the National Seminar on "Innovations in Agrophysics for Green Agriculture" will be organised at ICAR-IIWM, Bhubaneswar, during 22-24 January 2026. The Green Revolution successfully bridged the wide gap between the supply and demand of food grains leading to an increasing production trend to meet the food requirement of the Country. Moreover, there is a need to reduce the potential lag between irrigation potential created and utilized through judicious water saving technologies to enhance agricultural water productivity. On the other hand, concerted efforts should be made to manage unrestricted use of other natural resources, high external inputs, intensive cropping patterns and monoculture practices, which have caused food and environmental security problems. In this context, application of agro-physics techniques such as drones, remote sensing, simulation modelling, integrated sensing systems, AI, and machine learning, etc., for developing smart and green agriculture under different themes are pertinent and appropriate for the Seminar. It is expected that the participants in the Seminar, drawn from different spheres of agricultural science, will share their expertise and experience to widen their knowledge horizons in the proposed area to assist stakeholders. I am confident that the deliberations of the Seminar will help to formulate strategies and create an ecosystem of collaborative work culture to ensure food-water-energy and environment security of the Country.

I wish the Seminar a great success.

(Arjamadutta Sarangi)

कृषि भौतिक संभाग
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अध्यक्ष
Dr. Subash Nataraja Pillai
Head

Ref. No. AP / ....

Dated 19-01-2026

Message

I am pleased to learn that the Indian Society of Agrophysics is organizing a National Seminar on "**Innovations for Green Agriculture**" during 22–24 January 2026 at ICAR–IIWM, Bhubaneswar. Impressive achievements have been made worldwide in the prudent management of natural resources and in enhancing agricultural productivity. However, burgeoning demographic pressures pose formidable challenges to policymakers, scientists, and all other stakeholders, including implementing agencies, in ensuring sustainable livelihoods for the teeming millions.

Agricultural production systems are inherently complex, encompassing diverse disciplines within agricultural sciences. Agrophysicists have played a pivotal role in addressing the complexities of the soil–plant–atmosphere continuum and in developing appropriate technologies for varied agro-climatic conditions. The integration of advanced remote sensing, drone-based observations, and data analytics provides unprecedented opportunities for real-time monitoring, precise assessment, and efficient management of soil, water, and crop resources. Harnessing these digital technologies will strengthen evidence-based decision-making, optimize input use, and enhance the resilience and sustainability of natural resource management systems.

I am confident that the delegates attending this Seminar will engage in meaningful discussions on critical issues related to smart agriculture, climate change, and resource management, and will evolve viable, resource-efficient research and development strategies to ensure food and nutritional security, generate employment opportunities, and contribute to doubling farmers' income.

I wish the National Seminar every success in its endeavours.

SUBASH NATARAJA PILLAI

President, Indian Society of Agrophysics

Contents

National Seminar on Innovations in Agrophysics for Green Agriculture
22-24 January 2026 at ICAR-IIWM, Bhubaneswar

Agrophysics Enabled Innovations for Green Agriculture

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ABSTRACT

Green Agriculture (GA) represents a paradigm shift from the input-intensive production models towards a holistic, resource-efficient "system of systems" that balances productivity with agricultural stewardship. Often described as Green Agriculture 2.0 or Agriculture 5.0, this approach treats soil as a living ecosystem and uses digital intelligence to deliver 'right practice at right place at right time'. Recent advancements across agrophysics and allied domains fare accelerating this shift: (i) Soil physics innovations such as soil conditioners (e.g., hydrogel-in suitable contexts) combined with real-time soil-water sensing (e.g., TDRT) can improve irrigation decisions and reduce avoidable losses; (ii) remote sensing and phenotyping, especially hyperspectral imaging and UAV platforms support earlier detection of crop stress and spatially explicit management; (ii) AI-enabled microclimate and disease-risk models are improving the timing and targeting of interventions; (iv) biophysical models (e.g., radiative transfer modelling) to strengthening non-destructive diagnosis of canopy status; and (iv) nanotechnology and advanced formulations (including controlled or slow-release mechanisms)aim to raise nutrient-use-efficiency while reducing off-site impacts. The next step is integration, supported by precision Agri-Tech, conservation tillage, and Integrated Nutrient/ Pest Management (INM/IPM), addresses the urgent drivers of resource scarcity and climate change. By transforming farms into carbon sinks and reducing water/fertilizer waste by 30–50%, these innovations bolster the economic resilience of smallholders and protect non-renewable soil resources. Despite technological maturity, the transition to a global "Green Agriculture 2030" agenda necessitates: (1) Explainable AI (XAI) to foster farmer trust through transparent decision-support; (2) Interdisciplinary Standardization for data interoperability; (3) Circular Bioeconomy Integration via on-farm bio-refineries; and (4) Data Democratization to bridge the digital divide for small-scale farmers. The evolution toward Green Agriculture 2.0 provides a credible pathway to food and nutritional security within planetary boundaries.

Key words: Green Agriculture 2.0, Agriculture 5.0, Agrophysics, Precision Agriculture, Sustainable Resource Management, Carbon and Water Strewardship

Introduction

The global agricultural landscape is currently undergoing a profound transformation, moving away from a yield-only paradigm toward Green Agriculture (GA) – crop and livestock production that is both environmentally sustainable, climate-responsive, and mindful of long-term resource integrity. Unlike traditional intensive farming, GA prioritises Green Solutions (GS), a suite of agribusiness practices that reduce waste, lower emissions, and protect soil and water while sustaining farm incomes.

To understand the current trajectory of agricultural innovation, one must look back to the linguistic and scientific roots of the term. The phrase "Green Revolution" was first coined by William

Gaud in 1968. At that time, it described a rapid surge in crop production driven by high-yielding varieties (HYVs), mineral fertilizers, and synthetic agrochemicals. While this movement was instrumental in saving millions from famine in developing nations, its definition of "green" was rooted in productivity rather than ecology.

Today, "green" increasingly means environmentally friendly, efficient, and restrained use of chemical protectants, coupled with stewardship of soil and ecosystems (Struik and Kuyper, 2017). This modern agriculture is not just a production system, but as a commitment to the rights of future generations to inherit healthy ecosystems and adequate resources.

A central pillar of this transition is soil conservation because preserving the physical integrity of the soil is essential to maintaining yields and ensuring that farming activities remain viable in the long term (Nwachukwu, 2023). This transition represents a move toward a resource-efficient economy, where the primary goal is reducing waste and achieving low-carbon outcomes. While the original Green Revolution addressed food security through R&D and shortened cropping periods for high-volume output, GA seeks to harmonize these food security goals with environmental health.

Central to the realization of GA is the integration of modern, energy-compliant machinery. In the wake of the global energy transition, GA focuses on innovations that utilize renewable energy sources rather than fossil fuels . This creates what can be described as a "pyramid of innovation" on the energy mix, ensuring that global food production is adequate to meet human needs while fully complying with contemporary regulations on low-carbon emissions.

Agriculture 5.0 extends digital agriculture beyond automation: it places humans, ecosystems, and sustainability at the centre, combining artificial intelligence (AI), robotics, Internet of Things (IoT), big data analytics, and cyber–physical systems with agroecological logic to achieve highly efficient, adaptive, and sustainable food production systems. Unlike Agriculture 4.0, which mainly emphasised precision and automation, Agriculture 5.0 places humans, ecosystems, and sustainability at the centre of technological innovation, aligning production goals with environmental stewardship and climate resilience.

GA 2.0 complements Agriculture 5.0 by providing the ecological and systems-based foundation, treating soil as a living ecosystem and focusing on low-carbon pathways, resource-use efficiency, and circular bioeconomy principles. Agriculture 5.0 provides digital intelligence and automation, while GA 2.0 provides the ecological logic, enabling farming systems that are productive, climate-smart, and environmentally regenerative rather than input-intensive (Struik & Kuyper, 2017).

The Green Agriculture 2030 vision represent a forward-looking global framework aligned with the UN Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). It emphasizes transforming agricultural systems into low-carbon, resource-efficient, and biodiversity-enhancing systems, while ensuring food and nutritional security (Canton, 2021).

Key components of Green Agriculture 2030 include:

1. Climate-smart soil and water management
2. Digital and AI-enabled decision support (Agriculture 5.0)
3. Circular bioeconomy and nutrient recycling
4. Carbon sequestration and ecosystem service enhancement

By integrating advanced technologies with agroecological principles, Green Agriculture 2030 envisions farms as carbon sinks, data-driven ecosystems, and engines of rural resilience, rather than mere production units (Koohafkan et al., 2012).

Technological Components for Green Agriculture

A practical GA strategy combines field-ready agroecological practices with agrophysics-enabled measurement, modelling, and decision-support. The six core, field-ready pillars of GA includes:

Pillar 1. Biological nutrient pathways and soil biology

This pillar focuses on reducing dependence on energy-intensive external inputs by strengthening biological nutrient cycling and the soil–plant–microbe interface.

(a) Biological and Symbiotic Nitrogen Fixation (SNF)

A fundamental pillar of Green Agriculture involves the reduction of energy-intensive synthetic chemical inputs through the utilization of legumes, which host specialized rhizobia bacteria in root nodules to convert atmospheric nitrogen (N_2) into ammonia (NH_3) (Uebersax et al., 2023). This natural process significantly reduces the agricultural carbon footprint by lowering reliance on synthetic nitrogenous fertilizers—a major source of greenhouse gas emissions—while maintaining long-term soil fertility and structural integrity.

(b) Rhizosphere Engineering and Mycorrhizal Synergies

Advanced sustainable agriculture focuses on the "rhizosphere," where plants form symbiotic relationships with Arbuscular Mycorrhizal Fungi (AMF) to mobilize phosphorus and micronutrients that are otherwise chemically "locked" in the soil. Through chemical signaling, such as the release of flavonoids, plants can actively recruit beneficial microbes to create a "suppressive soil" environment that naturally inhibits pathogens without the use of synthetic soil fumigants.

Pillar 2. Diversity-driven resilience

This pillar builds resilience by increasing functional diversity in time and space—within fields, across seasons, and at landscape scale—so pest, disease, and climate risks are buffered biologically rather than chemically.

(a) Rotational Diversity and Spatiotemporal Cropping Windows

Sustainable development leverages "short-season" crops with growth cycles of 90–100 days to maximize land-use efficiency and implement "rotational diversity," which allows for the integration of multiple species within a single season. This scientific strategy effectively suppresses the buildup of soil-borne pathogens and foliar diseases by extending the interval between similar crop types (typically at least three years), thereby reducing the need for chemical intervention.

(b) Integrated Cover Cropping and Bio-protection

The integration of cover crops, such as small grains or oilseed radish, serves as a vital component for protecting the agricultural ecosystem during off-seasons by reducing soil erosion and improving soil organic matter and aggregate stability upon incorporation. Beyond physical protection, these crops function as biological controls or "trap crops" for specific pests like nematodes, substituting synthetic pesticides with ecological competition and bio-protection.

(c) Genetic Biodiversity and Abiotic Stress Resilience

The utilization of extensive genetic biodiversity, including landraces and diverse market classes, provides a biological "buffer" against climate instability and variable weather patterns. Scientific breeding programs focus on enhancing abiotic stress tolerance, specifically for drought, high temperatures, and waterlogging, to ensure that agricultural systems remain productive and resilient under changing environmental conditions.

(d) Integrated Pest Management (IPM) and Endogenous Defence

A core component of GA is "Endogenous Defence," which involves breeding genetic resistance to major viruses and fungi directly into the seed's DNA to minimise the requirement for synthetic sprays. By utilizing the host-plant resistance (HPR) found in natural landraces, scientists can develop cultivars that repel insects or inhibit fungal growth, thereby maintaining a cleaner water table by preventing chemical runoff and leaching.

(e) Landscape-Scale Agroecology and Spatial Management

Advanced sustainable development treats the landscape as an integrated system, managing semi-natural elements like hedges and vegetation strips to foster the natural enemies of pests. Spatial technologies, such as "push-pull" strategies, in which trap crops "pull" pests away while other plants "push" them out, enable effective pest management at a territorial scale, reducing the chemical load across entire agricultural regions.

Pillar 3. Soil physical protection and disturbance minimisation

(a) Conservation Tillage and Direct Seeding Technology

Green Agriculture prioritizes the preservation of soil architecture through minimal tillage or "no-till" practices, which are enabled by advanced machinery like direct seeders equipped with coulter discs. These technologies allow planting directly into living mulch or crop stubble, thereby preserving soil organic matter, protecting microbial diversity, and preventing the oxidation of soil carbon that typically occurs during mechanical disturbance.

(b) Carbon Sequestration and Soil Organic Carbon (SOC) Stabilization

Agricultural systems act as "Carbon Sinks" by utilizing high-biomass root systems that leave significant organic matter in the soil after harvest. When combined with no-till practices, this organic matter contributes to soil "crumb structure" (aggregation), which stabilizes soil organic carbon and prevents its release as CO2, effectively turning the farm into a tool for climate change mitigation.

Pillar 4. Precision water and nutrient stewardship

This pillar improves resource-use efficiency by aligning water and nutrient use with plant demand through physiology-informed traits, monitoring, and targeted management.

(a) Water Stewardship and Transpiration Efficiency

To adapt to increasing water scarcity, Green Agriculture employs climate-smart physiological traits such as enhanced stomatal regulation and deep-rooting architecture. These traits allow plants to maintain photosynthesis under moisture stress and to tap into lower soil-moisture profiles, effectively increasing water-use efficiency (WUE) and reducing dependence on intensive, energy-demanding irrigation systems.

(b) Phenomics, Predictive Breeding, and Precision Agriculture

The future of Green Agriculture relies on high-tech data integration, including the use of drones and sensors (phenomics) to monitor crop health in real time and ensure that inputs such as water or organic amendments are applied with extreme precision. By mapping genomes and utilizing predictive breeding, researchers can accelerate the development of sustainable cultivars, ensuring that the agricultural system remains responsive to future climate scenarios.

Pillar 5. Output efficiency and nutrition-sensitive goals

This pillar reframes productivity as *more value per unit resource*, including nutritional density, harvest efficiency, and energy-smart post-harvest chains.

(a) Biofortification and Nutritional Sustainability

Green Agriculture emphasizes "output efficiency" by maximizing the nutritional density of crops per unit of land through the selective breeding of varieties biofortified with essential minerals like Iron (Fe) and Zinc (Zn). By prioritizing the production of high-density proteins and bioavailable minerals, these systems reduce the environmental cost of nutrition and strengthen global nutritional security without increasing the ecological footprint.

(b) Energy-Efficient Harvest and Post-harvest Engineering

Advanced breeding for upright plant architecture facilitates direct mechanical harvesting in a single pass, significantly reducing fossil fuel consumption during the agribusiness process. Furthermore, selecting crop varieties that remain stable at higher moisture contents (e.g., 18%) reduces the energy demand for artificial, fossil-fuel-based grain drying, aligning the post-harvest chain with global energy transition regulations.

Pillar 6. Circular bioeconomy and by-product valorization

This pillar closes loops (biomass, nutrients, and value chains), so that the waste becomes a resource and the system's net footprint declines.

(a) Circular Bio-economy and By-product Valorization

Implementing a "zero-waste" approach, Green Agriculture focuses on the valorization of by-products, such as repurposing cellulose-rich straw and hulls into organic mulch, livestock feed, or raw materials for bio-plastics. Additionally, the extraction of secondary metabolites for pharmaceutical or food-preservation industries adds economic value to the farm without increasing its environmental footprint, closing the loop of the agribusiness process.

(b) Low-Carbon Life Cycle and Footprint Mitigation

Sustainability in agriculture is increasingly quantified through Life Cycle Analysis (LCA), which shows that leguminous and plant-based systems have the lowest negative environmental impacts across land use, energy consumption, and acidification potential. Integrating these low-impact crops into the agribusiness process results in a significantly smaller carbon footprint compared to intensive monocultures or animal-based production systems.

Together, these six pillars define the practice-first foundation of GA, but their performance and scalability increasingly depend on measurement, modelling, and timely decision-making. The next section highlights Agriculture 5.0 (enablers like sensing, remote monitoring, data analytics, and targeted mechanisation) that improve precision, reduce waste, and support risk-managed adoption. In this framing, advanced tools do not replace agroecological principles; they make them more reliable, site-specific, and verifiable.

Advanced Agrophysics Technologies enabling Green Agriculture 2.0

The transition from principles (six pillars) to field-scale performance depends on a practical technology stack that connects measurement (sensing), interpretation (diagnosis), decision-support, targeted action, and verification. Key enabling technologies and examples are summarised in Table 1, and the text below explains how these components function together as a coherent Agriculture 5.0 system without replacing agroecological foundations, but making them more precise, scalable, and outcome-verifiable.

A. Sense and observe: measuring soil-plant-atmosphere continuum

1. Hyperspectral Remote Sensing and Satellite Phenotyping

Effective landscape management is supported by advanced data capture technologies, including hyperspectral cameras mounted on satellites or drones that detect unique spectral signatures indicative of early-stage water or nutrient stress. Geographic Information Systems (GIS) and remote sensing enable mapping of landscape connectivity, identifying optimal locations for semi-natural buffers to facilitate the regional movement of beneficial insects and improve overall ecosystem services.

2. Hydrogel-Enhanced Matrices and Time Domain Reflectometry (TDR)

To combat water scarcity, hydrogels are used as soil amendments to increase water-holding capacity and plant-available water while reducing percolation losses. Complementing this, Time Domain Reflectometry (TDR) provides real-time, non-destructive monitoring of soil moisture to enable precision irrigation scheduling. Together, these tools improve water-use efficiency by up to 40%, preventing degradation like salinization under Agriculture 5.0 frameworks (Ahmed et al., 2015).

3. Precision Farming and Transgenic Solutions (data-enabled input synchronisation)

Precision farming integrates advanced sensors and data management systems to accurately synchronise agricultural inputs, such as water and nutrients, with forecasted global food demands, minimising waste (Wezel et al., 2014). Concurrently, the deployment of genetically modified (GM) or transgenic crops serves as a high-tech solution to achieve global food security by enhancing yield potential and biological resilience in the face of changing environmental pressures.

B. Diagnose and predict: converting signals into agronomic meaning

1. Biophysics and Radiative Transfer Models (RTMs) for Optimizing Solar Energy Capture

Biophysics employs Radiative Transfer Models (RTMs) to simulate solar radiation interactions with crop canopies, quantifying absorption and reflection to optimize planting geometry. Integrated with remote sensing, RTMs non-destructively assess crop vigor and biomass to maximize photosynthetically active radiation (PAR) use efficiency. This precision management enhances carbon-use efficiency and supports climate-smart production with minimal external inputs (Jacquemoud et al., 2009).

2. AI-Driven Microclimate Models for 14-Day Disease Forecasting

Modern meteorology utilizes machine learning to integrate weather variables, crop phenology, and pathogen cycles for field-scale, 14-day disease forecasting. In Green Agriculture, these AI systems replace prophylactic pesticide use with targeted interventions, reducing chemical loads and environmental contamination. These models are vital for managing fungal and bacterial threats within integrated pest management (IPM) and climate-resilient strategies (Liakos et al., 2018).

3. Phenomics, Predictive Breeding, and Precision Agriculture (diagnosis + prediction)

The future of Green Agriculture relies on high-tech data integration, including the use of drones and sensors (phenomics) to monitor crop health in real time and ensure that inputs such as water or organic amendments are applied with extreme precision. By mapping genomes and utilizing predictive breeding, researchers can accelerate the development of sustainable cultivars, ensuring that the agricultural system remains responsive to future climate scenarios.

C. Decide: decision-support that times and targets interventions

1. Precision Resource Management of Water and Nutrients

Sustainable development utilizes precision technologies such as drip irrigation to minimize water waste by matching crop-specific hydraulic demand in both time and space, which effectively mitigates soil salinization. Additionally, advanced management practices like split fertilization, Drip Irrigation increase nutrient uptake efficiency and prevent the contamination of ground and surface waters by applying fertilizers in strategically timed operations that align with the plant's developmental stages.

2. IoT-Enabled Smart Resource Cycles and Digital Twins

Sustainability is maintained through real-time feedback loops powered by the Internet of Things (IoT), utilizing in-situ biodegradable soil nano-sensors to monitor nitrogen and phosphorus levels. These data feed into dynamic "Digital Twin" models of the farm, enabling predictive simulations of crop rotations and automating "smart" irrigation systems that respond precisely to the plant's actual biological demand, thereby preventing resource leaching and runoff.

D. Act: targeted interventions and system redesign (field operations)

1. Mechanical Engineering for Agricultural System Redesign

The structural shift to sustainable no-till systems requires advanced mechanical engineering, specifically direct seeding technology where specialized seeders equipped with coulter discs or tines deposit seeds directly into living cover crops or mulch. This system redesign is further supported by innovative mechanical weed management tools that allow for non-chemical control, maintaining soil structure and organic matter without the heavy reliance on synthetic herbicides.

2. AI-Driven Bio-Robotics and Autonomous Management

The elimination of chemical herbicides is facilitated by AI-driven autonomous bio-robotics, which utilize computer vision and machine learning to distinguish between crops and weeds for precise laser weeding or mechanical hoeing. Swarm robotics, consisting of small, autonomous "field-bots", further optimize the system by performing micro-tasks such as targeted bio-pesticide application and split fertilization while significantly reducing soil compaction compared to conventional heavy machinery.

3. Bio-technological Innovations and Bio-inputs

The transition toward green agriculture emphasizes the substitution of synthetic chemicals with biological technologies, notably biofertilisers consisting of Plant Growth-Promoting Rhizobacteria (PGPR) that optimize nutrient availability at the seed or soil level. Furthermore, botanical pesticides derived from plant extracts like essential oils or pyrethrum offer a technological alternative to synthetic protectants, effectively controlling pests while minimizing deleterious environmental side effects.

4. Nanotechnology for Targeted Delivery of Biological Inputs

Nanotechnology enhances the efficacy of biological inputs through nano-encapsulation, in which natural pesticides and biofertilisers are encapsulated in biodegradable capsules to prevent UV degradation and environmental leaching. This technology ensures the controlled, slow release of active ingredients at the root tip or leaf surface, maximizing the efficiency of "green" inputs and significantly reducing the total volume of materials required for effective crop protection and nutrition.

5. Circular Bio-Refinery and Nutrient Recovery Technologies

To close the agricultural resource loop, circular bio-refinery technologies utilize advanced filtration and chemical processing to recover high-purity nitrogen and phosphorus from agricultural runoff and livestock waste. These reclaimed nutrients are subsequently reformulated into biofertilisers, transforming potential environmental pollutants into high-value resources that support the next cropping cycle within a zero-waste agribusiness framework.

6. Agro-Voltaic Systems and Energy-Food Dualism

Advanced sustainable development integrates renewable energy production with crop cultivation through agro-voltaic systems, where semi-transparent solar panels are installed above agricultural fields. This dual land-use technology generates clean energy while simultaneously creating a favourable micro-climate that reduces evapotranspiration and protects shade-tolerant crops, such as various legumes and leafy greens, from extreme heat and radiation stress.

E. Act: Redesigning biology (crop improvement as a technology action)

1. Precision Farming and Transgenic Solutions (genetic component)

Concurrently, the deployment of genetically modified (GM) or transgenic crops serves as a high-tech solution to achieve global food security by enhancing yield potential and biological resilience in the face of changing environmental pressures.

2. Rhizosphere Engineering and Ecological Breeding

Modern breeding strategies have shifted from high-input responses toward ecological synergy, specifically through rhizosphere engineering that selects for plant traits that enhance microbial activity, such as the Arbuscular Mycorrhizal Fungi (AMF) symbiosis. Targeted resistance breeding further utilizes hybrid and conventional techniques to develop cultivars resilient to pathogens and abiotic stressors, including significant water and nitrogen deficiencies, ensuring stability in low-input environments.

3. Precision Gene Editing (CRISPR/Cas9) for System Redesign

Beyond traditional transgenics, site-directed mutagenesis via CRISPR/Cas9 technology allows for the precise redesign of crop architecture to support sustainable practices like intercropping and relay cropping. By engineering plants to secrete specific carbon signals or altering their physical structure to improve light penetration for secondary cover crops, precision gene editing creates highly efficient plant-soil-microbe feedback loops that enhance systemic sustainability.

F. Verify and scale: outcome tracking and landscape integration

1. Chemical Signalling and Spatial Pest Management Technologies

Agroecological systems utilize the endogenous "chemical technology" of plants through allelopathic interactions, where natural exudates are harnessed for biofumigation to inhibit weeds and soil-borne diseases. Advanced spatial technologies, such as the push-pull strategy, employ trap crops to attract pests away from the primary crop while repellent plants push them out of the field, creating a complex biological defense perimeter that reduces the need for external pesticides.

2. Landscape-Scale Monitoring and Multi-Stakeholder Integration

Sustainable development operates at a territorial scale by integrating semi-natural landscape elements, such as vegetation strips and hedges, that bolster populations of natural pest enemies. Achieving biological control across diverse regions requires advanced, multi-stakeholder coordination and agreement, treating the landscape as an integrated socio-technical system in which territorial development ensures ecological continuity and resource conservation.

Table 1. Advanced tools and technologies for Green Agriculture

S. No.	Tool / Technology	Primary use	Origin Country	Key contribution	In-text Citation
1	Time Domain Reflectometry (TDR)	Soil moisture monitoring	USA	Real-time, non-destructive monitoring of soil water content; improves irrigation scheduling and water-use efficiency, contributing to 30–40% water savings.	Lakhiar *et al.* (2024)
2	Hyperspectral remote sensing	Stress-diagnostic	USA / EU	Early nutrient stress, water stress, and disease before visual symptoms; supports sub-meter resolution biophysical parameter retrieval for precision farming.	Thenkabail *et al.* (2019)
3	CRISPR/ Cas9 gene editing	Crop improvement	Japan / USA	Precise, site-directed mutagenesis for drought tolerance, nutrient-use efficiency, and intercropping-friendly plant architecture without foreign DNA insertion.	Hazrati *et al.* (2025)
4	Nano-/ controlled release fertilizers	Nutrient delivery	India / China	Improved nutrient-use efficiency by controlled and slow release; reduces fertilizer losses and environmental pollution by up to 50%.	Singh *et al.* (2024)
5	IoT-based soil sensors	Irrigation and fertigation	USA	Real-time data on soil moisture, temperature, and nutrient dynamics; enables smart irrigation and fertigation through decision-support systems.	Shahab *et al.* (2025)
6	AI-driven DSS	Farm management	USA	Weather, soil, and crop data integration to predict yield, disease outbreaks, and irrigation needs; enhances climate resilience and reduces input wastage.	Magaya *et al.* (2024)
7	Agrivoltaic systems	Energy–food co-production	Germany	Dual land use for solar energy and crop production; reduces evapo-transpiration and heat stress while generating renewable energy.	Sheikh and Mahod (2011)
8	Direct seeders/ No-till machinery	Conservation agriculture	Brazil	Soil structure preservation, increases soil organic carbon sequestration, and reduces fuel consumption and erosion under sustainable intensification systems.	Sharma *et al.* (2024)
9	Biofertilizers (PGPR, AMF)	Soil biology	Netherlands	Biological nitrogen fixation, phosphorus mobilization, and microbial diversity; reduces dependency on synthetic fertilizers.	Dzvene and Chiduza (2024)
10	UAV phenomics	Breeding and management	Australia	Accelerated breeding for stress tolerance and resource-use efficiency by high-throughput, non-invasive crop trait assessment.	Angidi (2025)
11	Autonomous weeding robots	Weed management	France	Machine vision and machine learning to identify and remove weeds mechanically or via laser, minimizing herbicide use.	Khan *et al.* (2025)

Contd...

S. No.	Tool / Technology	Primary use	Origin Country	Key contribution	In-text Citation
12	Digital twin of farms	Systems management	USA	Simulation of soil–crop–climate interactions to test management scenarios, improving long-term sustainability and risk management.	Tsakiridis *et al*. (2023)
13	Nano-sensors for soil nutrients	Micro-scale sensing	South Korea	Nitrogen and phosphorus dynamics in situ at micro-scales, enabling ultra-precise nutrient management.	Javed *et al*. (2022)
14	Push–Pull technology	Pest ecology	Kenya	Spatial crop arrangement to biologically control pests and enhance biodiversity, reducing chemical pesticide reliance.	Cordeau *et al*. (2024)

Challenges and constraints for scale-up

While technological and agroecological innovations provide a roadmap for sustainability, their implementation faces significant scientific, socio-economic, and systemic hurdles. The following points detail the core challenges and constraints that must be addressed to bridge the "sustainability gap."

1. Definition of Sustainability Thresholds and Tipping Points

A primary scientific challenge lies in identifying precise ecological thresholds beyond which farming technologies trigger irreversible "tipping-point" phenomena. Green Agriculture must operate within locally adaptable principles and boundaries that preserve the resilience of agroecosystems while ensuring food, energy, and technological sovereignty for rural communities (Koohafkan et al.,2012).

2. The Widening Sustainability Gap and Agroecological Engineering

There is a significant and growing disparity between current agricultural practices and the long-term requirements for an effective "life-support system." Closing this "sustainability gap" (Fischer et al., 2007) requires a transition from minor efficiency gains to "agroecological engineering" (a term coined by Vanloqueren and Baret 2009) a nascent scientific process focused on the deliberate design of productive and resilient systems from the ground up.

3. The Yield-Stability Trade-off and Global Food Security Demands

Transitioning to green or organic models typically results in a yield deficit of 20% to 35% compared to conventional intensive farming. This productivity gap, combined with a 15% lower stability in yield performance, poses a major geopolitical constraint as global food production must increase significantly to meet the needs of a projected 9 billion people by 2050 (Boix-Fayos & De Vente 2023)

4. Nitrogen Acquisition Bottlenecks in Synthetic-Free Systems

The elimination of mineral fertilizers creates a critical constraint regarding adequate nitrogen supply. Relying exclusively on Biological Nitrogen Fixation (BNF) through legume rotations reduces the total land area available for primary non-legume crops, which inherently limits the overall caloric productivity of the agricultural system.

5. Land-Use Competition and the Expansion Constraint

Because green systems often produce lower yields per hectare, they require approximately 1.6 units of additional land to match the output of conventional systems. This land demand creates a direct conflict with conservation goals, as converting forests, grasslands, or wetlands into arable land results in the loss of vital ecosystem services and sequestered carbon.

6. Mandatory Dietary Shifts and Nutritional Sensitivity

The viability of Green Agriculture is scientifically linked to changes in human consumption patterns, particularly the reduction of animal products and grain-fed livestock. Sustainable food systems require a transition toward "nutrition-sensitive" agriculture that focuses on high-quality, protein-rich plant sources (like legumes) to keep food production within defined planetary boundaries.

7. Systemic Resource Depletion through Post-Harvest Food Waste

Approximately one-third of global food production is lost or wasted, representing a massive depletion of natural resources—including water, nutrients, and energy—that never reach the consumer. Addressing this waste is a mandatory scientific complement to greening production, as current waste levels in some regions account for up to 30% of available daily calories.

8. Socio-Economic Inequity in Food Distribution and Access

Sustainability is often constrained by a narrow focus on production metrics that ignores the complexities of food distribution and economic access. Reducing agricultural inputs can lead to higher commodity prices and trade reductions, potentially increasing food insecurity in vulnerable regions like Africa unless accompanied by measures to incentivize better distribution and technological sovereignty.

9. The Risk of Environmental Externalization and Outsourcing

Green policies in high-income regions carry the risk of "outsourcing" environmental degradation to countries with lower standards. If a region reduces its local chemical use but continues to import goods produced via deforestation and intensive pesticide use elsewhere, the net global environmental impact is shifted rather than reduced.

10. Paradigmatic Tensions between Agroecology and Sustainable Intensification

A major conceptual challenge exists between Agroecology (AE), which takes a holistic, social, and locally adapted approach, and Sustainable Intensification (SI), which focuses on optimizing large-scale efficiency. Reconciling these two paradigms is essential for creating a unified framework that can scale green practices without losing the socio-political integrity of farming communities.

Conclusion

Green Agriculture (GA) is no-longer a 'low-input' idea. It is into a measurement- and intelligence-enabled redesign of farming systems, aligned with Agriculture 5.0. This paradigm shift prioritizes the coordinated development of economic productivity and environmental preservation by treating the soil as a vital living ecosystem. Technological Synergies are Critical for Resource Efficiency:

The integration of cross-disciplinary innovations such as Nano-encapsulated nutrients, AI-driven microclimate models, and Time Domain Reflectometry (TDR) has demonstrated the capacity to increase fertilizer efficiency by 50% and improve water retention by 40%. These technologies allow for sub-meter resolution in crop monitoring, ensuring that inputs are applied only when biologically necessary. Agroecological Resilience through Biological Engineering: Transitioning away from synthetic chemicals relies on harnessing natural biological processes, specifically Symbiotic Nitrogen Fixation (SNF) and Rhizosphere Engineering. By utilizing Plant Growth-Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF), agricultural systems can naturally enhance nutrient availability and suppress pathogens, reducing the environmental footprint and acidification potential. Mitigation of the "Sustainability Gap": A primary constraint remains the "sustainability gap", the disparity between current production needs and long-term ecological requirements. While green systems often face a yield deficit of 20-35% compared to conventional models, this can be mitigated through "agroecological engineering", which combines high-tech precision with regenerative practices like conservation tillage and biofortification to maximize "output efficiency" per unit of land. Systemic Redesign for Climate Neutrality: Transforming farms into carbon sinks requires a holistic redesign, including the use of Agro-voltaic systems for dual land use and the implementation of a Circular Bio-economy that repurposes biomass waste into bio-plastics or organic mulch. These innovations are essential for meeting the global "Green Agriculture 2030" agenda.

In summary, the transition to a sustainable global food system necessitates a dual-track approach that reconciles Sustainable Intensification (SI) with Agroecology (AE). To achieve global scale, the scientific community must prioritize Explainable AI (XAI) to build farmer trust, establish universal carbon standards, and implement robust biosafety frameworks for nanomaterials. With these enablers and appropriate safeguards for biosafety and standards, GA 2.0 offers a realistic pathway to food and nutritional security while protecting soil and water resources for future generation.

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Agrophysics for Green Agriculture: Science Driving Sustainability and Resilience

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ABSTRACT

Green agriculture has emerged as a transformative paradigm to reconcile the dual objectives of enhancing agricultural productivity and ensuring environmental sustainability under increasing climate variability and resource constraints. In India, where agriculture underpins food security, livelihoods, and ecological stability, the urgency of transitioning toward greener agricultural systems has intensified in response to climate change, land and water degradation, declining factor productivity, and rising energy footprints. Agrophysics, an interdisciplinary science that applies physical principles to agricultural systems, provides a quantitative and process-based foundation for understanding soil–plant–atmosphere interactions, water and energy fluxes, crop microclimate, and ecosystem functioning. This manuscript synthesizes the conceptual, methodological, and applied contributions of agrophysics to green agriculture, with particular emphasis on Indian agro-ecological contexts and policy priorities. It discusses how agrophysical approaches enable efficient resource use, climate adaptation and mitigation, precision agriculture, and evidence-based policy support. Special attention is given to national missions and policy frameworks, including the National Mission on Sustainable Agriculture, India's climate commitments, and the vision of Viksit Bharat @2047. The manuscript also outlines future research directions emphasizing digital agrophysics, systems modeling, and integration with artificial intelligence. Overall, agrophysics is positioned as a cornerstone discipline for advancing green, resilient, and low-emission agricultural systems in India.

Introduction

Agriculture continues to play a pivotal role in India's socio-economic fabric, contributing significantly to food security, employment, and rural livelihoods. Despite structural shifts in the economy, nearly half of India's population remains dependent on agriculture and allied sectors, underscoring its strategic importance for national stability and inclusive growth. Indian agriculture has achieved remarkable gains in food production since independence, particularly during the Green Revolution era; however, these gains have been accompanied by unintended environmental and resource-related consequences (Pathak, 2014).

Excessive dependence on groundwater irrigation, imbalanced fertilizer use, declining soil organic carbon, and loss of agrobiodiversity have emerged as major challenges across intensively cultivated regions (Lal, 2015). Climate change has further compounded these stresses through rising temperatures, altered precipitation regimes, increased frequency of extreme weather events, and heightened production risks (Aggarwal, 2008). Rainfed systems, which constitute nearly 60 percent of India's cultivated area, are particularly vulnerable to climate variability, threatening livelihoods and food security (Pathak, 2014).

In response, green agriculture has gained prominence as a holistic approach that integrates productivity, sustainability, and resilience. Green agriculture seeks to optimize resource use, reduce environmental footprints, and enhance ecosystem services while maintaining or increasing crop yields (Pretty *et al.*, 2018). However, translating this vision into practice requires robust scientific understanding and quantitative tools to evaluate system performance under diverse agro-climatic conditions.

Agrophysics provides precisely this foundation. By applying the laws of physics to agricultural systems, agrophysics enables rigorous measurement, modeling, and optimization of soil, water, energy, and atmospheric processes that govern crop growth and ecosystem functioning (Baver *et al.*, 1972; Hillel, 2004). In the Indian context, strengthening agrophysical research and its integration with policy and practice is essential for achieving sustainable intensification and long-term resilience.

Green Agriculture: Concept, Principles, and Indian Relevance

Green agriculture represents an integrated framework that balances agricultural productivity with environmental conservation, climate resilience, and socio-economic sustainability (FAO, 2017; Pretty *et al.*, 2018). It emphasizes efficient use of land, water, nutrients, and energy, while minimizing negative externalities such as greenhouse gas emissions, soil degradation, and water pollution.

At a conceptual level, green agriculture views farms as managed ecosystems where biophysical processes interact dynamically with management decisions and climatic drivers. This systems perspective is particularly relevant for India, characterized by diverse agro-climatic zones, smallholder-dominated farming systems, and high pressure on natural resources. Green agriculture integrates approaches such as conservation agriculture, climate-smart agriculture, agroecology, precision farming, and renewable energy use (FAO, 2017).

In India, green agriculture aligns strongly with national development priorities, including food and nutritional security, doubling farmers' income, water-use efficiency, and climate adaptation. Initiatives such as the National Mission on Sustainable Agriculture and the National Water Mission explicitly recognize the need for resource-efficient and climate-resilient farming systems. However, effective implementation requires scientific tools to assess trade-offs, quantify benefits, and guide context-specific interventions.

Agrophysics plays a critical role in operationalizing green agriculture by providing quantitative metrics of sustainability, such as water productivity, energy-use efficiency, soil carbon dynamics, and microclimatic regulation (Monteith & Unsworth, 2013). These metrics enable objective evaluation of green practices across regions and scales, facilitating evidence-based decision-making.

Agricultural Physics and Green Agriculture

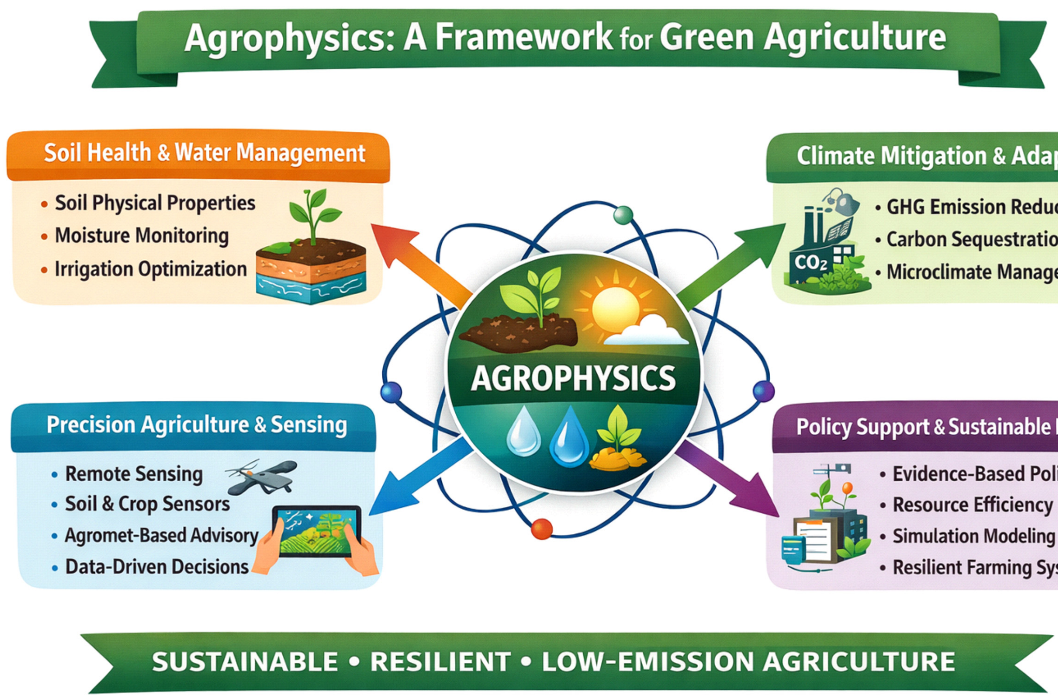
Agricultural physics, or agrophysics, applies fundamental physical principles to agricultural systems, focusing on the soil–plant–atmosphere continuum (SPAC). It encompasses processes such as soil water movement, heat and radiation transfer, gas exchange, evapotranspiration, and crop microclimate (Baver *et al.*, 1972; Hillel, 2004).

Green agriculture depends inherently on optimizing these processes. For example, improving water-use efficiency requires understanding soil hydraulic conductivity, root-zone moisture dynamics, atmospheric evaporative demand, and crop physiological responses (Monteith &

Unsworth, 2013). Agrophysical measurements and models enable precise irrigation scheduling, reducing water losses while sustaining yields.

Agrophysics also bridges crop physiology and environmental physics, providing insights into radiation interception, canopy temperature regulation, and transpiration efficiency. These insights are critical for designing climate-resilient cropping systems, particularly under heat and drought stress. In addition, agrophysical modeling supports scenario analysis, allowing assessment of management options under future climate conditions (Aggarwal, 2008).

By converting sustainability goals into measurable variables, agrophysics ensures that green agriculture is grounded in scientific rigor rather than normative aspirations alone. The different components and a framework for Agro-Physics for Green Agriculture is shown in Figure.



Soil Health, Water Dynamics, and Resource Conservation

Soil health is a foundational pillar of green agriculture, influencing water availability, nutrient cycling, root growth, and carbon sequestration. Agrophysics contributes to soil health assessment by quantifying physical properties such as bulk density, porosity, aggregate stability, infiltration rate, and soil water retention (Hillel, 2004).

In Indian soils, long-term intensive cultivation has led to compaction, reduced infiltration, and declining organic matter in many regions (Lal, 2015). Agrophysical studies help diagnose these issues and design interventions such as residue management, reduced tillage, and organic amendments. Soil moisture dynamics, analyzed through agrophysical models, guide efficient irrigation and drought management strategies.

Water scarcity is a critical constraint in Indian agriculture. Agrophysics supports water conservation through precise estimation of evapotranspiration, soil moisture monitoring, and groundwater recharge processes (Monteith & Unsworth, 2013). These tools underpin micro-irrigation, deficit irrigation, and rainwater harvesting strategies central to green agriculture (Pathak, 2014).

By linking soil physical health with water productivity, agrophysics directly contributes to sustainable intensification and long-term resilience of agricultural systems.

Climate Change Mitigation and Adaptation

Agriculture is both a victim and contributor to climate change. Agrophysics enables quantification of greenhouse gas fluxes, soil carbon sequestration, and surface energy balance, providing a scientific basis for mitigation strategies (Lal, 2015).

Agrophysical measurements of soil temperature, moisture, and gas diffusion inform estimates of carbon dioxide, methane, and nitrous oxide emissions from agricultural fields (Pathak, 2014). Conservation tillage, residue retention, and improved water management can be evaluated quantitatively for their mitigation potential.

Adaptation strategies also benefit from agrophysical insights. Crop microclimate modification through mulching, shelterbelts, and altered canopy architecture can reduce heat stress and improve water-use efficiency. Modeling tools allow assessment of crop responses under future climate scenarios, guiding varietal selection and management decisions (Aggarwal *et al.*, 2008).

Thus, agrophysics serves as a bridge between climate science and practical adaptation–mitigation strategies in agriculture.

Precision Agriculture and Digital Agrophysics

Precision agriculture represents a technological manifestation of green agriculture, aiming to apply inputs at the right place, time, and quantity. Agrophysics underpins precision agriculture through sensor-based measurement of soil moisture, temperature, radiation, and crop stress indicators.

Remote sensing and proximal sensing technologies translate agrophysical variables into spatially explicit information, enabling site-specific management (Monteith & Unsworth, 2013). Digital agrophysics integrates these measurements with crop models and decision-support systems, enhancing resource-use efficiency and reducing environmental footprints.

In India, digital agriculture initiatives increasingly rely on agrophysical data streams to support advisories, insurance, and early warning systems. This integration enhances transparency, scalability, and impact of green agriculture interventions.

Policy Support and India-Specific Linkages

Agrophysics provides an evidence base for policy formulation and evaluation. Quantitative indicators such as water productivity, energy efficiency, and emission intensity support monitoring of national missions including NMSA and India's climate commitments.

Agrophysical research informs region-specific recommendations, enabling decentralized planning aligned with agro-climatic realities. Integration with digital governance platforms enhances policy responsiveness and accountability. Complete set of Agrophysics-Based Components and Indicators of Green Agriculture is given in Table 1.

Table 1. Agrophysics-Based Components and Indicators of Green Agriculture

Dimension of Green Agriculture	Agrophysics Contribution	Agromet-Based Advisory Role	Simulation & Modelling Tools	Key Outcomes for Green Agriculture
Soil Health & Soil Physical Quality	Measurement of soil texture, structure, bulk density, porosity, soil moisture dynamics, infiltration and hydraulic conductivity	Advisories on tillage timing, soil moisture–based sowing windows, and residue management	Soil water balance models, HYDRUS, DSSAT–soil modules	Improved soil structure, enhanced root growth, reduced land degradation
Water Use Efficiency & Irrigation Management	Quantification of soil–plant–atmosphere water fluxes, evapo-transpiration, capillary rise	Irrigation scheduling advisories using real-time weather and soil moisture	AquaCrop, SWAT, FAO-56 ET models	Reduced water use, improved water productivity, climate-resilient irrigation
Crop Growth & Productivity	Canopy energy balance, radiation interception, root–soil interaction	Weather-based crop stage advisories, frost/heat stress warnings	Crop simulation models (DSSAT, APSIM, WOFOST)	Stable yields with reduced resource inputs
Climate Change Adaptation	Microclimate modification, soil thermal regime studies, mulching and residue physics	Short- and medium-range advisories for extreme weather events	Climate–crop integrated models, downscaled climate scenarios	Reduced climate risk, enhanced system resilience
Climate Change Mitigation	Measurement of soil carbon sequestration, GHG fluxes (CO_2, CH_4, N_2O)	Advisories on low-emission practices (alternate wetting and drying, residue retention)	GHG estimation models, DNDC, RothC	Lower emission intensity, carbon-neutral farming systems
Precision Agriculture & Digital Farming	Sensor-based soil moisture, temperature, salinity and compaction assessment	Field-specific advisories using weather–sensor integration	Digital twins, AI-driven crop–soil models	Input optimization, reduced environmental footprint
Agrometeorological Advisory Services (AAS)	Physical interpretation of weather impacts on soil and crop processes	Location-specific, crop-stage-specific advisories	Decision support systems integrating weather and crop models	Risk-informed farm decisions, enhanced adaptive capacity
Nutrient Use Efficiency	Soil physical control on nutrient movement, leaching and uptake	Fertilizer timing advisories based on rainfall and soil moisture	Nutrient cycling modules in crop models	Reduced nutrient losses, higher fertilizer efficiency
Sustainable Cropping Systems	Energy and mass balance studies in diversified and conservation systems	Cropping system advisories under variable climate	System-level simulation models	Sustainable intensification with ecological balance
Policy & Planning Support	Generation of physical indicators (water productivity, carbon stocks)	Climate-smart advisories for regional planning	Scenario analysis and impact assessment models	Evidence-based policies for Green Agriculture
Monitoring & Evaluation (STI Indicators)	Development of agrophysical indicators (soil moisture index, energy efficiency)	Validation of advisory effectiveness	Integrated assessment frameworks	Science-based tracking of green agriculture outcomes

Future Research Directions

Future agrophysical research must embrace digital twins, artificial intelligence, and multi-scale modeling to address complex sustainability challenges. Integration of high-resolution sensing with process-based models will enable predictive and adaptive management under climate uncertainty.

Interdisciplinary collaboration with social sciences and economics is essential to translate agrophysical insights into adoption pathways and policy impact. Capacity building and institutional strengthening remain critical priorities for the coming decades.

Conclusions

Agrophysics is central to the scientific realization of green agriculture. By providing quantitative understanding of soil–plant–atmosphere processes, agrophysics enables efficient resource use, climate resilience, and environmental stewardship. In India, strengthening agrophysics within research, policy, and practice is essential for achieving sustainable and inclusive agricultural transformation aligned with national and global goals.

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National Seminar on Innovations in Agrophysics for Green Agriculture
22-24 January 2026 at ICAR-IIWM, Bhubaneswar

Innovative Technologies for Crop and Soil Health Management in Green Agriculture

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ABSTRACT

Green agriculture promotes environmentally sustainable, resource-efficient, and socially responsible farming systems, emphasizing soil and crop health as central determinants of productivity, resilience, and ecosystem stability. Conventional blanket input practices often lead to nutrient imbalances, declining factor productivity, and environmental degradation. In contrast, precision, digital, and knowledge-driven technologies enable site-specific, preventive, and data-informed crop and soil management. Soil health underpins sustainable agriculture, with integrated physical, chemical, and biological properties supporting nutrient cycling, water regulation, and ecosystem services. Advanced soil sampling strategies, automation, and GPS/GIS-based fertility mapping enhance the accuracy of nutrient recommendations, enabling integrated nutrient management, conservation agriculture, and carbon sequestration. Precision agriculture tools—including remote sensing, hyperspectral imaging, LiDAR, and machine learning–based Soil Test Crop Response models—support variable-rate nutrient applications and optimized yield predictions. Digital platforms and decision support systems provide location-specific advisories for nutrient, water, and pest management, integrating Soil Health Card data for consistent yet site-tailored recommendations. Sensor technologies and soil spectroscopy allow rapid, non-destructive soil assessment, while Agricultural Internet of Things (AIoT) and automation facilitate real-time monitoring and precision input application. Climate-smart and weather-adaptive interventions further enhance resilience under variable conditions. Despite these advancements, challenges such as inadequate infrastructure, limited adoption by smallholders, policy gaps, and data governance issues constrain scalability. Strengthening institutional linkages, capacity building, policy incentives, standardization, and applied research are essential for wider adoption. Integrating precision tools, digital platforms, and participatory governance can optimize input use, enhance crop productivity, and sustain soil health, fostering resilient, productive, and environmentally responsible agricultural systems

Key words: Precision nutrient management, Decision support systems, Agricultural Internet of Things, Soil spectroscopy, Climate adaptation, Site-specific interventions.

Introduction

Green agriculture emphasizes environmentally sustainable, resource-efficient, and socially responsible farming systems that maintain productivity while conserving natural resources. Crop and soil health are central to this paradigm, as they determine agricultural resilience, yield potential, and ecosystem stability. Conventional approaches relying on blanket input application often lead to nutrient imbalances, declining factor productivity, and environmental degradation (Dey, 2016). In contrast, precision, digital, and knowledge-based tools have emerged as transformative enablers, facilitating preventive and data-driven management of crops and soils.

Soil Health as the Foundation of Green Agriculture

Soil health reflects the integrated physical, chemical, and biological properties that sustain plant growth, regulate water and nutrient cycles, and provide ecosystem services. Constraints such as soil structure degradation, organic carbon depletion, and declining microbial activity pose significant challenges to sustainable agriculture (Dey & Bhattacharyya, 2021). Innovative technologies enable site-specific assessment of soil properties, balanced nutrient application, and monitoring of dynamic soil parameters, thereby supporting integrated nutrient management (INM), conservation agriculture, and carbon sequestration practices. Advanced soil sampling strategies—including grid, directed, and participatory sampling—combined with GPS tagging, improve the reliability of soil fertility maps and nutrient recommendations (ProSoil Newsletter, 2018; Sekhon *et al*., 2017). Automation in sampling through unmanned ground vehicles or robotic platforms enhances efficiency, safety, and data quality, allowing for more frequent monitoring of soil health (Valjaots *et al*., 2018; Dey & Bhattacharyya, 2021).

Precision Agriculture Technologies

Precision agriculture has shifted field management from uniform to site-specific interventions. Remote sensing and satellite imagery provide cost-effective and reliable assessments of canopy nitrogen (N) status and crop health over large areas, enabling early-season and spatially variable N management. Hyperspectral and LiDAR-based indices facilitate accurate prediction of crop nitrogen content, supporting variable-rate applications. Application of machine learning in remote sensing has been applied successfully under field condition (Arab *et al*., 2021). Machine learning and artificial neural network (ANN)-driven Soil Test Crop Response (STCR) models further integrate soil moisture variability to optimize nutrient application, improving yield predictions and nutrient use efficiency (Saha *et al*., 2021).

GPS/GIS-based soil fertility mapping allows the development of customized fertilizers by identifying management zones, target yields, and nutrient requirements (Dey *et al*., 2017a; Basavaraja *et al*., 2016). For instance, site-specific formulations have been deployed for maize and potato in Bihar and West Bengal, incorporating macro- and micronutrients such as S, Zn, and B, improving nutrient use efficiency and crop profitability (Dey, 2019). Interpolation techniques such as ordinary kriging, inverse distance weighting, and spline methods are essential for assessing soil properties in unsampled locations, allowing high-resolution spatial decision-making (Kanwaria *et al*., 2021).

Digital Platforms and Decision Support Systems

Digital innovations have revolutionized access to soil, crop, weather, and advisory services. Platforms such as KISAAN 2.0 consolidate over 300 agriculture-related applications into a single, multilingual interface, simplifying access to validated agronomic recommendations (Dey, 2019). Decision support systems (DSS), including DSSIFER and Nutrient Expert®, provide location-specific fertilizer prescriptions based on soil test values, STCR equations, and targeted yield concepts (Dey, 2016). Mobile applications further enhance real-time advisory dissemination, enabling farmers to make informed decisions regarding nutrient management, irrigation, and crop protection (Dey, 2019). Integration of Soil Health Card data into these systems supports uniform recommendations across administrative regions while allowing for site-specific adjustments.

Digital tools and DSS also support integrated pest and disease management (IPM/IDM) by enabling early detection, monitoring, and advisory-based intervention. Minimizing pesticide use preserves beneficial soil organisms, prevents contamination of water and soil, and maintains agro-ecosystem balance, contributing to environmentally sustainable farming.

Sensor Technologies and Soil Spectroscopy

Emerging sensor-based technologies facilitate rapid, non-destructive assessment of soil properties. Ground-based, proximal, and aerial sensors measure soil moisture, nutrient content, and plant health in real time, supporting data-driven fertilization and irrigation decisions (Chaudhari *et al*., 2022; Erler *et al*., 2020). Spectroscopic methods, including mid-infrared (MIR), near-infrared (NIR), diffuse reflectance (DRS), and portable X-ray fluorescence (XRF), enable rapid and environmentally friendly estimation of soil parameters such as organic carbon, pH, texture, and available K (Dey *et al*., 2017b; Hati *et al*., 2022). These approaches reduce reliance on labor-intensive laboratory analyses and facilitate landscape-scale digital soil mapping for precision nutrient management.

Agricultural Internet of Things (AIoT) and Automation

The Agricultural Internet of Things integrates AI, machine learning, cloud computing, and IoT-enabled devices for holistic farm management (Dey & Bhattacharyya, 2021). IoT-based platforms monitor soil moisture, nutrient status, and crop health, delivering precision recommendations for fertilizer and irrigation management. Variable-rate technology (VRT) automated via AIoT ensures optimal input distribution, reducing costs, enhancing efficiency, and supporting sustainable soil and crop management (Fig. 1).

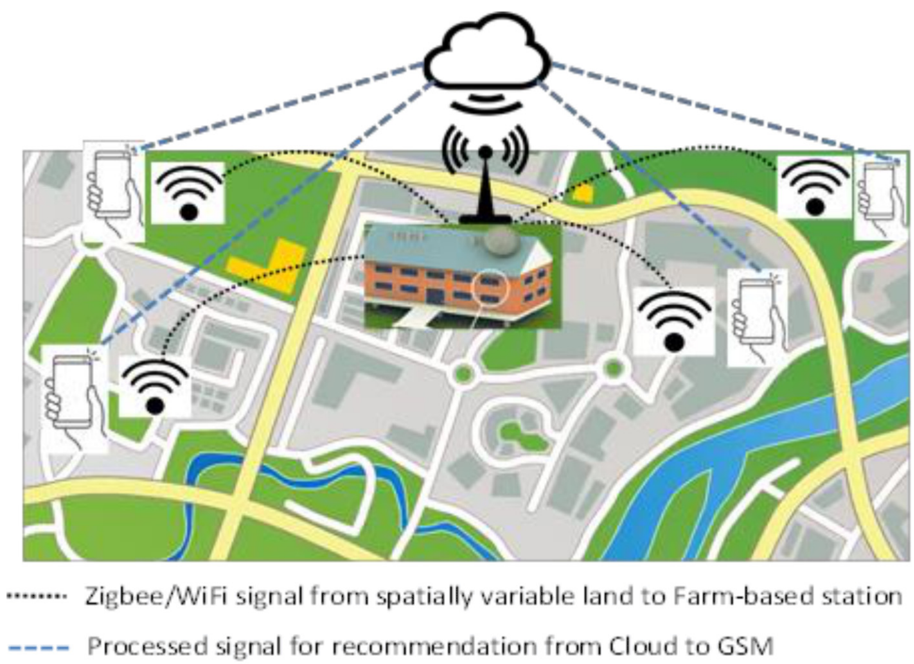

Fig. 1. Use of IoT for doorstep delivery of plant nutrient recommendations

Climate-Smart and Weather-Based Technologies

Climate variability influences nutrient availability and soil moisture dynamics, directly affecting crop productivity. Weather-based advisories integrated with digital platforms and precision tools allow farmers to adjust sowing dates, irrigation schedules, and nutrient applications to minimize climate-related risks. Such adaptive strategies align with sustainable intensification objectives by improving water-use efficiency and protecting soil fertility under stress conditions (Dey & Bhattacharyya, 2021).

Challenges

Despite rapid advancements in precision agriculture, digital platforms, and sensor-based technologies, several policy and implementation challenges limit their full potential in promoting green agriculture. Key policy issues include inadequate infrastructure for high-resolution soil and crop data collection, lack of standardized protocols for soil health assessment and digital data integration, limited financial and institutional support for smallholder adoption, and gaps in capacity-building among farmers and extension personnel (Dey & Bhattacharyya, 2021; Chaudhari *et al*., 2022). Furthermore, data ownership, privacy, and interoperability remain critical concerns in the deployment of IoT and AI-driven agricultural platforms.

Another challenge lies in bridging the gap between research outputs and field-level adoption. While STCR models, soil fertility maps, and DSS tools have demonstrated site-specific advantages, uptake is constrained by weak linkages between farmers, extension services, and digital advisory systems (Dey, 2019). The heterogeneity of smallholder farms, varying literacy levels, and regional socio-economic disparities necessitate context-specific strategies for technology dissemination. Additionally, regulatory frameworks need to support customized fertilizer formulations, biofertilizers, and nanofertilizer use while ensuring environmental safety and sustainability (Basavaraja *et al*., 2016).

Conclusion

Innovative technologies—ranging from precision remote sensing and AI-driven models to digital platforms, spectroscopy, and IoT-based solutions—are essential for green agriculture. By enabling data-driven, site-specific, and climate-smart decision-making, these technologies optimize input use, enhance crop productivity, and sustain soil health. Continued integration of technological advancements with institutional frameworks, participatory sampling, and capacity building will be pivotal for building resilient, productive, and environmentally responsible agricultural systems.

Way-forward

- **Strengthening Institutional Mechanisms:** Establish coordinated platforms linking research institutions, extension agencies, digital service providers, and farmer collectives to facilitate knowledge transfer and continuous feedback.
- **Capacity Development and Training:** Organize targeted training programs and on-field demonstrations to enhance farmer awareness, digital literacy, and proficiency in precision nutrient and water management.
- **Policy Incentives and Subsidies:** Provide financial incentives, including subsidies for sensors, AIoT-enabled devices, and variable-rate applicators, to encourage adoption among resource-constrained smallholders.

- **Standardization and Data Governance:** Develop uniform standards for soil testing, spectroscopy calibration, and digital data interoperability, while ensuring secure data management practices.
- **Research and Development:** Promote applied research in AI-driven predictive models, spectral libraries for diverse soil types, and climate-resilient nutrient management strategies that integrate local agroecological knowledge.
- **Integration with Climate-Smart Agriculture:** Align technological interventions with climate adaptation policies, focusing on carbon sequestration, water-use efficiency, and resilient cropping systems.

By addressing these policy gaps and fostering an enabling environment, technology-driven green agriculture can move beyond pilot-scale interventions toward scalable, sustainable, and inclusive adoption. An integrated approach combining precision tools, digital platforms, and participatory governance will enhance resource-use efficiency, crop productivity, and long-term soil health, contributing to resilient agro-ecosystems and food security.

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Road Map of Agricultural Water Management for Green Agriculture – An Overview

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Water management in agriculture sector in the coming decades will play a vital role to meet the escalating food demand of the Country. In this context, judicious management of irrigation water will be required to not only save water but also to bring more area under assured irrigation. In India, the irrigation sector would require 40% more water from the present level of 588 billion cubic meter to feed the burgeoning population by 2025. Moreover, till 2023-24, about 56% of the net cropped area is irrigated and 44% of area is not having any irrigation facility. Further, due to growing competition for water among domestic and industrial sectors, there is a greater challenge in the agricultural sector to produce more food from less water, which can be achieved by increasing Crop Water Productivity (CWP). In India, the major source of irrigation is through use of ground water (61%) followed by canal systems (25%). Moreover, there is 18% gap between the irrigation potential created and utilized as reported by XIth plan, which need to be minimized further. Therefore, keeping in view of all these scenarios and to accomplish the prime objective of *Pradhan Mantri Krishi Sinchai Yojana* (PMKSY) *i.e.* "Prime Minister Irrigated Agriculture Scheme" ensuring supply of irrigation water to each farmers' field and implement different water saving technologies. Such activity will ensure "*per drop more crop*" and the key challenge to accomplish this would primarily be the judicious irrigation water management. Moreover, under the changing climate scenarios the agricultural water management technology needs to be restructured to be applied at regional scales targeting specific problem of the region.

Judicious irrigation water management can be accomplished by deciding proper irrigation scheduling using soil moisture sensors for different crops and cropping systems, measurement of irrigation water and its supply based on the crop water requirement and integration of geospatial tools and modelling techniques to develop mobile applications, Decision Support systems (DSS) and IT based protocols for enhancing water productivity in agriculture (CSSRI, 2014, Sarangi *et al.*, 2004). Besides this, the crop water demand based rostering in the canal commands can enhance the water productivity and ensure supply of water to tail end reach of the command (Sagar *et al.*, 2016). Integration of crop model and climate generator can assist in deciding the future irrigation requirement for sustaining the crop yield under changing climate (Abedinpor *et al.*, 2014). Besides this the water footprint estimation at watershed scale can assist in delineation of regions for taking of suitable crops to reduce the water footprint and enhance water productivity (Mali *et al.*, 2017). Also, the ground water and energy nexus impacting the environment can be reduced by deciding the operation schedule of ground water pumping based on the crop water requirement (Patle *et al.*, 2016).

It was observed that use of soil moisture deficit (SMD) based irrigation scheduling resulted in saving of irrigation water and enhancing water productivity in experimented cereal crops *viz*. rice, wheat and maize. Validated crop models were used for prediction of crop yield under varying irrigation water requirement and under changing climate, which would assist the stake holders in deciding the irrigation schedules for different crops under varying soil texture and climatic parameters. Different scenarios of crop yield and water productivity were generated to guide the stakeholders and policy makers for judicious agricultural water management. Estimation of regional crop coefficients of different crops by using the weighing type field lysimeters assisted in computation of irrigation water requirement at regional scale and for water budgeting investigation to save water and enhance water productivity. Use of soil moisture sensor and vadose zone modelling studies provided information of soil moisture dynamics in the crop root zone leading to timing and quantification of irrigation water leading to increased water productivity.

Recent trends in Agricultural Water Management (AWM) research

Recent developments has benefitted in **i**mproved water use efficiency, enhanced soil health and reduced soil erosion, increased resilience to climate change, biodiversity preservation, sustainable land use, reduced flooding and water pollution, cost-effective and long-term solutions, improved agricultural productivity, economic and social benefits besides use of modern technology. However, such development has limitations and challenges faces in terms of high initial costs, lack of awareness and education, technical expertise, climate variability, long-term maintenance, conflicting interests and stakeholder coordination, data availability and its quality, policy and regulatory Barriers etc.. Some of the recent developments are:

Smart irrigation technologies

A major development in soil and water conservation engineering, smart irrigation systems maximize water use in farming operations. These systems use technology to increase crop yields, decrease water waste, and improve irrigation efficiency while taking environmental sustainability into account. The following are some significant features and advancements in smart irrigation systems such as Sensor-Based Irrigation (Soil Moisture Sensors, Weather Sensors, Evapotranspiration (ET) Sensors), Automated Control Systems (Centralized Control Systems, Programmable Timers),Water Use Efficiency(Drip Irrigation, Subsurface Drip Irrigation (SDI), Variable Rate Irrigation (VRI)), Integration with Climate and Environmental Data(Remote Sensing and Satellite Imagery, Weather Forecast Integration),AI and Machine Learning (Predictive Analytics, Automated Decision-Making),Cloud-based Management(Data Collection and Remote Monitoring, Data Visualization and Reporting),Water conservation and environmental impact (Reduction in Water Waste, Sustainable Agriculture). The digital water measuring device for field channels in ca canal command and the AWD based irrigation scheduler using the ultrasonic sesnsor is shown in Fig.1.

Soil moisture accounting and management

An essential component of soil and water conservation engineering as well as sustainable agricultural methods is soil moisture management. For crop health and water conservation, especially in areas with water shortage, proper soil moisture management helps guarantee that plants receive enough water while reducing water waste. In addition to increasing soil fertility and lowering

Fig. 1. The AWD based Irrigation scheduler and the digital water measuring device for open field channel installed in the experimental sites

the chance of erosion, efficient soil moisture management also raises total land production. Some of the devices and technologies are: Soil Moisture Sensors and Monitoring Technologies (Tensiometers, Capacitance Sensors, Time-Domain Reflectometry (TDR), Wireless Sensors and IoT Integration), Use of Remote Sensing and Satellite Technology (Satellite Imagery, Drones and UAVs), Water Retention Techniques (Hydrogels, evaporation suppressants and Superabsorbent Polymers, Water-Retaining Soil Amendments), Irrigation Management (Smart Irrigation Systems, Subsurface Drip Irrigation (SDI), Rainwater Harvesting), Soil Moisture Retention through Mulching (Organic Mulches, Plastic Mulches), Soil Structure and Water Infiltration (No-Till and Reduced-Till Farming, Cover Cropping, Infiltration Barriers), Climate-Smart Soil Moisture Management (Adaptive Water Management, Drought-Tolerant Crops), Soil Moisture Modeling and Predictive Analytics (Modeling Soil Moisture Dynamics using AI/ml techniques), Groundwater Recharge and Management (Managed Aquifer Recharge (MAR), Soil Moisture-Based Groundwater Monitoring). The capacitance based soil moisture sensor is installed in the field (Fig. 2).

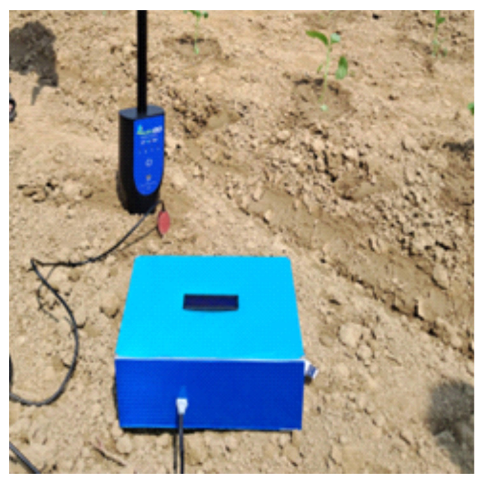

Fig. 2 Capacitance based soil moisture sensor

Erosion control techniques

In order to prevent soil erosion, some of technologies are Vegetative Erosion Control (Cover Cropping, Grassed Waterways, Riparian Buffers), Physical and Structural Erosion Control (Terracing, Check Dams and Retaining Walls, Gabions, Silt Fences), Mulching (Organic Mulches, Hydraulic Mulching), Soil Stabilization with Geo-textiles and Other Materials (Geotextiles, Erosion Control Mats, Soil Binders and Stabilizers), Water Management Techniques (Contour Ploughing and Farming, Infiltration Trenches, Diversion Ditches), Bioengineering Techniques (half moon terraces, small pits, tree Planting and Agroforestry), Gully Plugging and Stream bank Protection, Vegetative and Structural Combinations, Education on Best Management Practices (BMPs) (Landowner Education besides Incentives for Conservation)

Sustainable water harvesting practices

Techniques for gathering, storing, and managing water resources in an ecologically conscious way are known as sustainable water harvesting practices. These methods are intended to maximise water efficiency while lessening the influence on ecosystems and natural water cycles. Some of the practices include *viz.* Rainwater Harvesting (Roof-Top Harvesting, Rainwater Harvesting Pits or Cisterns, Harvesting Rainwater in Agricultural Fields), Surface Water Harvesting (Ponds and Reservoirs, Check Dams and Earthen Dams, Swales and Trenches), Groundwater Recharge and Management (Recharge Pits and Trenches, Infiltration Galleries, Managed Aquifer Recharge (MAR)), Water Conservation and Efficiency Measures (Drip/drip tapes/ sub surface drip Irrigation Systems, Sprinkler Irrigation, Water-Saving Technologies), Contouring and Land Management (Contour Plowing and Terracing, Agroforestry, Cover Cropping), Desalination and Water Recycling (Desalination, Wastewater Recycling), Rainwater Harvesting for Small-Scale Agriculture (Microcatchment Systems, Water Harvesting with Raised Beds), Integrated Water Resource Management (IWRM) (Comprehensive Planning, Community-Based Water Harvesting Projects), Building Resilience to Climate Change(Climate-Smart Water Harvesting, Restoration of Watersheds), Urban Water Harvesting(Green Roofs, Urban Ponds and Lakes, Permeable Pavements); Nano-clay and composite rubber material lining of farm ponds.

Soil carbon sequestration

The process of absorbing and retaining atmospheric carbon dioxide (CO_2) in the soil by means of physical, chemical, and biological processes is known as soil carbon sequestration. By lowering the atmospheric concentration of CO_2, a primary cause of global warming, this technique is essential to limiting climate change. Some of the practices to enhance soil carbon sequestration are *viz.* reduced or No-Tillage Farming, Cover Cropping, Agroforestry, Organic Matter Addition (Composting), Rotational Grazing, Agroecological Practices, Reforestation and Afforestation, Wetland Restoration, Increased Crop Diversity besides cropping in polyhouses.

Climate smart water management

The integrated method of managing water resources in a way that is efficient in terms of water usage and adaptive to the effects of climate change, while also meeting the more general objectives of sustainable development and water security, is known as climate-smart water management (CSWM). In light of shifting climatic patterns, including an increase in droughts, floods, and erratic rainfall, this strategy helps guarantee that water resources are managed in a way that can sustain ecosystems, economies, and communities. Components of CSWM are *viz.* Efficient Irrigation Systems, Water-Efficient Technologies, Grey water Recycling, Leak Detection and Repair, Flood Management, Drought Management, Enhanced Weather and Climate Forecasting, Wetland Restoration and Protection, Watershed Management, Agroecology and Green Infrastructure, Cross-Sector Coordination, Water Allocation and Governance, Community Involvement, Smart Water Meters and IoT enabled solutions, Desalination, Cloud-Based Water Management Systems, Artificial Recharge of Groundwater.

Integrated watershed management (IWM)

A comprehensive strategy for managing a watershed's resources, integrated watershed management (IWM) emphasizes the conservation and sustainable use of land, water, and associated ecosystems. In order to guarantee that natural resources are managed effectively and fairly while fostering environmental preservation, social cohesion, and economic growth, IWM places a strong emphasis on cooperation between stakeholders (government organizations, local communities, environmental organizations, etc.). Key components of IWM are Water Resource Management (Water Allocation, Water Quality Monitoring, Watershed Hydrology, Groundwater recharge), Soil Conservation (Erosion Control, Sustainable Agricultural Practices), Vegetation and Forest Management (Afforestation and Reforestation, Riparian Buffer Zones), Community Involvement and Governance (Stakeholder Participation, Capacity Building), Monitoring and Data Collection (Geospatial Technologies, Hydrological Modeling, Climate Data acquisition and assimilation)

The future of irrigation water management in India looks promising, driven by advancements in technology, government initiatives, and the growing awareness of environmental sustainability. Nonetheless, implementation of different agricultural water management technologies for enhancing water productivity *viz.* crop water demand based irrigation scheduling; supply of measured quantity of water as required by crop at different growth stages; use of micro irrigation method; modification in the existing rotational water supply schedule (*i.e warabandi*) in canal commands based on the crop water demand based approach; development of water foot print based conjunctive water use plan for judicious use of both canal and ground water resources; use of appropriate soil moisture conservation, ground water recharge techniques and planting methods; bio-engineering measures for moisture conservation of rainfed and irrigated systems; implementation of deficit irrigation protocols in the region of less water availability; advocating Direct Seeded Rice (DSR) and System of Rice Intensification (SRI) cultivation methods in place of conventional rice cultivation method; crop diversification and selection of appropriate cropping system based on soil health, water and climate of the region and shifting to integrated farming systems are some of the technologies which need to be up-scaled for saving appreciable quantity of water. Thus, the saved water can be used for bringing more area under irrigation to meet the objectives of PMKSY. Besides this, implementation of technologies for use of saline water in irrigation and renovation of waterlogged and saline regions will assist in enhancing food grain production. Further, renovation of existing irrigation infrastructure and construction of new dams and canal systems for distribution of water to farmers' fields are necessary to increase the area under canal commands in different States of the Country. However, to accomplish these tasks, there is need of structures and low cost water measuring devices for measurement of irrigation water in open field channels and development of crop specific irrigation schedules to enhance water productivity of irrigated agriculture. In this context, development of low cost water measuring devices for field channels, standardization of soil moisture sensors and water measuring devices pertaining to crop specific irrigation schedule, use of geospatial tools, modelling techniques and development of Decision Support Systems (DSS) (Fig.3), big data analysis and smart mobile phone compatible applications under present and future changing climate will assist the stakeholders in not only enhancing water productivity but also in attaining sustainability in irrigated agriculture.

Managed Aquifer Recharge (MAR) techniques for groundwater recharge

As MAR techniques involve the intentional storage of water into an aquifer for subsequent recovery or for environmental benefits, considerable amount of research work in recent years has been carried out to alleviate the water crises as well as other related purposes. Some techniques for MAR are *viz.* Spreading methods to create ponds and basins to increase the contact area between

Fig. 3. DSS for enhancing water productivity in rice-wheat cropping system

surface water and soil; In-channel modifications through construction of check dams to slow down water flow and enhance infiltration; Well and borehole recharge to use open wells and shafts to recharge groundwater directly; Induced infiltration to use bank and dune filtration to recharge aquifers indirectly; Winter recharge project through use of surplus runoff water to restore depleted aquifers; Storm water or runoff capture to capture, store, and infiltrate storm water on floodplains, farmlands, and infiltration basins.

Trend of Water Productivity of selected crops

At the basin scale, IWMI developed a crop dominance map to identify areas dominated by rice, wheat, rice–wheat rotation, or mixed cropping systems. This map was synthesized using the following datasets such as Global Land Cover Characteristics Database (USGS), IWMI Global Irrigated Area Map (GIAM), MODIS-based South Asia rice map, Time-series MODIS NDVI data, Ground-truth surveys and crop rotation information. The remaining mixed agricultural areas were classified using unsupervised clustering (ISODATA), supported by crop growth signatures derived from NDVI and crop coefficient (Kc) curves. WP generated upto 2020 using the calculator were used in the Multivariate Adaptive Regression Spline (MARS) model to generate for short term projections upto 2035. The analysis revealed distinct historical trajectories and divergent future forecasts for the Physical Water Productivity (PWP) of four major crops: Wheat, Maize, Rice, and Soybeans. The non-linear spline approach identifies critical "hinge points" where the rate of productivity change shifted significantly due to technological or management interventions. Wheat and Maize exhibited the most aggressive growth in water productivity. Wheat showed a sharp inflection point around 2015, the productivity gradient steepened significantly, as evidenced by the model coefficient of 0.030 in the basis function. As per the projected estimate, by 2035, Wheat is projected to achieve the highest PWP of approximately 1.6 kg/m^3. Whereas, maize maintained a steady and strong upward trend consistently outperforming Rice and Soybeans, with a projected 2035 value exceeding 1.4 kg/m^3. Rice demonstrates a consistent but more moderate improvement in PWP compared to the coarse grains. The model identifies a hinge point in 2005, after which the growth rate improved slightly. Despite this progress, Rice remained in the mid-tier of productivity, forecasted to reach around 0.8 kg/m³ by 2035. However, soybeans in contrast to the cereal crops exhibited a downward trend. After a period of relative stability, the model identifies a negative shift starting around mid of 2012. The negative coefficient in the spline equation (-0.009max(0, Y - 2012.5)) indicated that water use efficiency for soybeans is decreasing, with the forecast suggesting a drop toward 0.15 kg/m³ by 2035 (Table 1). Adoption of water saving techniques by selection of appropriate planting methods and use of micro irrigation and automation of canal commands will enhance water productivity of different crops in the Country.

Moreover, the road map on enhancing the water productivity of majority of crop would rely on the judicious irrigation scheduling which can be automated by use of integrated sensing systems; modernization of canal commands using IoT enabled water measuring devices, UGPL besides SCADA and DSS enabled canal automation; upscaling of micro irrigation with biofertigation; Adoption of micro-irrigation in secondary storage reservoirs in canal commands and water harvesting structure in watersheds; crop diversification; upscaling of AWD and DSR rice planting methods to replace the conventional methods; renovation of defunct water bodies; design and implementation of location specific groundwater recharge structures through managed aquifer recharge (MAR) in different drainage basins; development of low cost technologies for purification of grey water and its use in agriculture; standardization of protocols of voluntary carbon market and ecosystem services for green agriculture; irrigation schedules for natural and organic farming under different AERs of the Country; water and nutrient management in hydroponics and aquaponics systems under vertical farming; water budgeting at state level and targeting of potential GW recharge and WHS using model fusing techniques besides capacity building of stakeholders and strengthening the water user associations (WUA) and work in a convergence mode in collaboration with State line departments (Fig. 4).

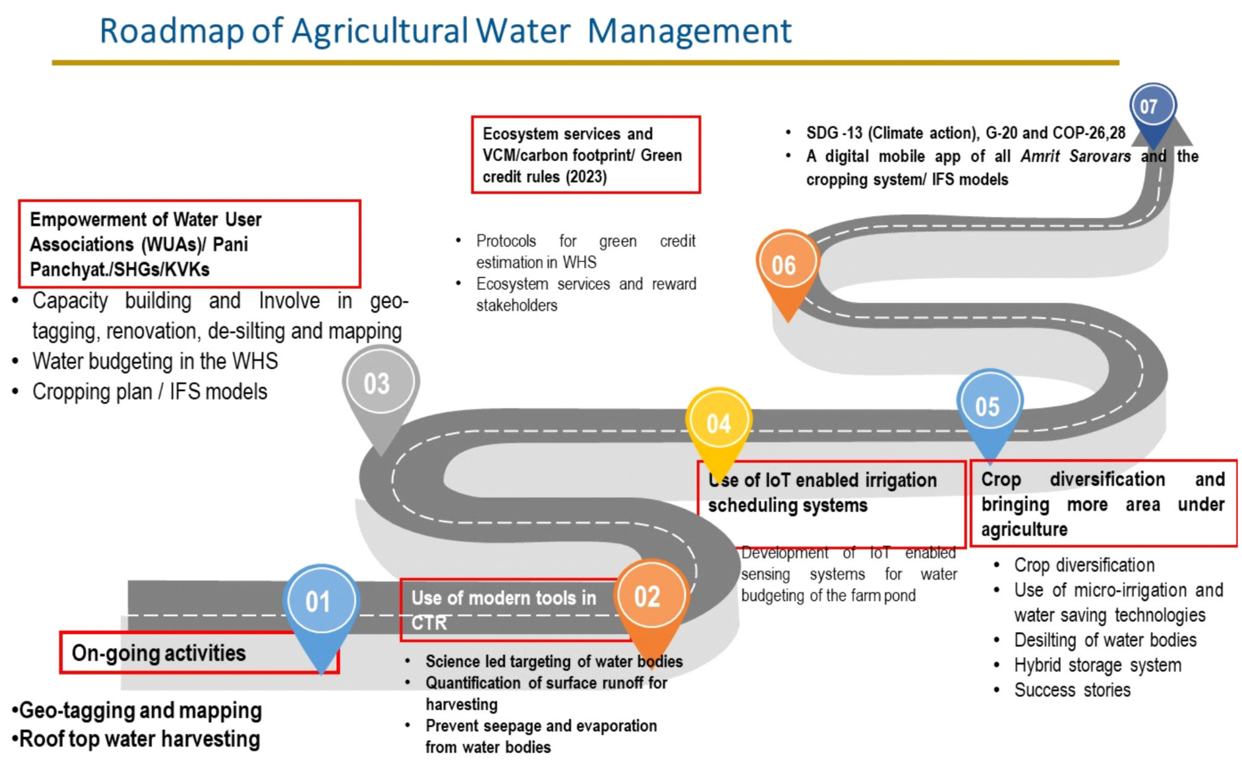

Fig. 4. Road map of agricultural water management to enhance water productivity

Table 1. Summary Table of Model Dynamics

Crop	Change point	Growth Intensity after the change point	2035 Predictions
Wheat	2015	Highest	Rapid Increase
Maize	2007	High	Strong Increase
Rice	2005	Moderate	Steady Increase
Soybean	2012	Negative	Declining

Conclusions

Integrated management of soil-water-vegetation resources in a watershed system not only enhance its productivity in terms of food, fiber, fodder, fish and fuel resources but also enhances the ecology and health of the watershed. To accomplish this, the first step is to identify suitable location of soil and water conservation measures in the watersheds followed by quantification of runoff and sediment generation rate, volume of runoff besides its spatio-temporal variability in the delineated watershed systems. To accomplish this, the geospatial tools (GPS, GIS, RS) and modelling techniques along with Decision Support systems can be used for data acquisition, analysis and interpretation of the geomorphologic, soil, water and vegetation related parameters influencing the generation of surface runoff and sediment from watershed systems. The basic premise of "better information leads to better decision" is cherished through use of the modern data acquisition tools. Moreover, Government of India programmes *viz. Pradhan Mantri Krishi SinchayeeYojana* (PMKSY), Soil Health Management through Soil Health Cards, National Watershed Management Project (NWMP), Catch the Rain (CTR) initiatives by MoJS, Atal Bhujal Yojana (ABY), Digital agriculture etc are also supporting in accomplishment of soil and water conservation activities in the Country. Such activities and its suitable implementation in the watershed system would enhance the ecosystem and heath of the region leading to enhancement of socio-economic status of the stakeholders. Protocols for quantification of ecosystem services and voluntary carbon credits based on green agriculture will assist in rewarding and motivating different stakeholders towards ensuring food, water, energy and environment security leading to attainment of sustainable development goals (SDGs) and net zero emission.

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Resilient Farming Systems for Green Agriculture: Integrating Diversification, Technology, and Climate Adaptation

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Introduction

Global agriculture faces an unprecedented convergence of challenges arising from population growth, climate change, environmental degradation, and socio-economic pressures. With the global population projected to reach 9.7 billion by 2050 (United Nations, 2019), food production will need to increase by approximately 56% relative to current levels (Van Dijk *et al*., 2021). Achieving this target under increasing climate variability necessitates not only productivity enhancement but also substantial improvements in resource-use efficiency and system stability.

Conventional intensification strategies have contributed significantly to yield gains over past decades; however, these gains have often been accompanied by soil degradation, groundwater depletion, biodiversity loss, and increased greenhouse gas emissions. Consequently, the long-term sustainability of such systems has been widely questioned. In response, *green agriculture* has emerged as a transformative paradigm that prioritizes environmental integrity, efficient resource use, and climate compatibility while maintaining farm profitability and livelihoods.

Within this paradigm, *resilient farming systems* play a central role. Rather than focusing exclusively on yield maximization, resilience-oriented systems emphasize stability, adaptability, multifunctionality and efficient resource use. Such systems are designed to buffer agricultural production against climatic, ecological, and economic shocks while enabling adaptive and transformative responses when prevailing practices become unsustainable. These considerations are particularly salient in India, where climate variability, resource degradation, smallholder dominance, and market uncertainties intersect to create acute vulnerabilities. Thus there is a need to understand trade-offs, adoption barriers, and institutional constraints that limit large-scale implementation, particularly in smallholder-dominated systems. Building on this synthesis, a systems-oriented framework is proposed to guide future research, policy formulation, and investment strategies aimed at accelerating transitions toward resilient and green agricultural systems under climate change.

Rationale for Resilient Farming Systems in the Indian Context

The imperative for resilient farming systems is especially pronounced in agriculture-dependent economies such as India, where climate risks, resource constraints, and socio-economic vulnerabilities converge. Persistent farmer distress—manifested in high incidences of indebtedness and farmer suicides—has been linked to crop failures, price volatility, and dependence on external inputs. The dominance of simplified production systems, particularly the rice–wheat monoculture, has further exacerbated these challenges.

While the rice–wheat system has played a critical role in national food security, its long-term sustainability is increasingly questioned due to declining factor productivity, excessive groundwater extraction, soil nutrient imbalances, and reduced employment opportunities. Moreover, globalization and trade liberalization under the World Trade Organization (WTO) regime have exposed Indian farmers to heightened price risks and international competition. Although these changes have stimulated the expansion of high-value horticultural and livestock products, they have simultaneously increased income instability among smallholders.

In this context, crop and livelihood diversification emerges as a fundamental risk-management strategy. Diversification into horticulture, livestock, agroforestry, and allied enterprises has been shown to stabilize farm incomes, generate higher on-farm employment, and enhance ecological sustainability. Additionally, the deployment of climate-resilient crop varieties with diversified genetic traits is increasingly recognized as essential for maintaining productivity under changing climatic conditions.

These strategies align closely with the principles of climate-smart agriculture (CSA), which integrates productivity enhancement, climate adaptation, and greenhouse gas mitigation. Practices such as reduced tillage, residue management, carbon sequestration, and data-driven crop management exemplify the operationalization of resilience within green agriculture frameworks. Despite demonstrated benefits, adoption remains constrained by limited awareness, restricted access to finance and technology, and inadequate institutional support, underscoring the need for targeted policy and investment interventions.

Conceptualizing Resilience in Farming Systems

Resilience in agricultural systems is inherently multidimensional and context-specific. It is commonly conceptualized through three interrelated capacities:

- **Absorptive capacity:** the ability of a system to withstand climatic shocks—such as droughts, floods, or heat stress—without significant loss of function.
- **Adaptive capacity:** the ability to adjust management practices, resource allocation, and decision-making in response to gradual or abrupt changes.
- **Transformative capacity:** the ability to shift toward fundamentally different production systems when existing configurations become ecologically or economically unsustainable.

Green agriculture aligns closely with this framework by promoting low-input systems, circular resource flows, ecosystem service enhancement, and climate mitigation. Farming system resilience thus serves as a conceptual bridge between productivity objectives and long-term environmental stewardship.

Drivers of the Transition towards Resilient Farming System

Climate Change and Variability

Increasing frequency and intensity of extreme climatic events have amplified yield variability and production risks across agro-ecological zones. Empirical evidence indicates that diversified and knowledge-intensive systems exhibit lower interannual yield fluctuations compared to simplified monocultures, thereby enhancing production stability under climate uncertainty.

Resource Scarcity and Environmental Degradation

Groundwater depletion, declining soil organic carbon, and nutrient imbalances pose significant threats to agricultural sustainability. Resilient systems prioritize soil–water–nutrient interactions and emphasize efficiency and regeneration rather than input intensification.

Socio-economic Constraints

Smallholder farmers dominate Indian agriculture but face constraints in capital, information access, and risk-bearing capacity. Consequently, resilience is not merely a biophysical attribute but also a socio-economic imperative with strong equity and livelihood dimensions.

Resilient Farming Systems for Green Agriculture are rooted in ecological balance, much like a tree sustained by strong and adaptive roots. By integrating diversification, soil and water stewardship, and climate-responsive technologies, these systems enhance stability, resource efficiency, and regenerative capacity (Fig. 1). Such an approach enables agriculture to withstand climatic stresses, adapt to change, and sustainably support livelihoods while preserving ecosystem health.

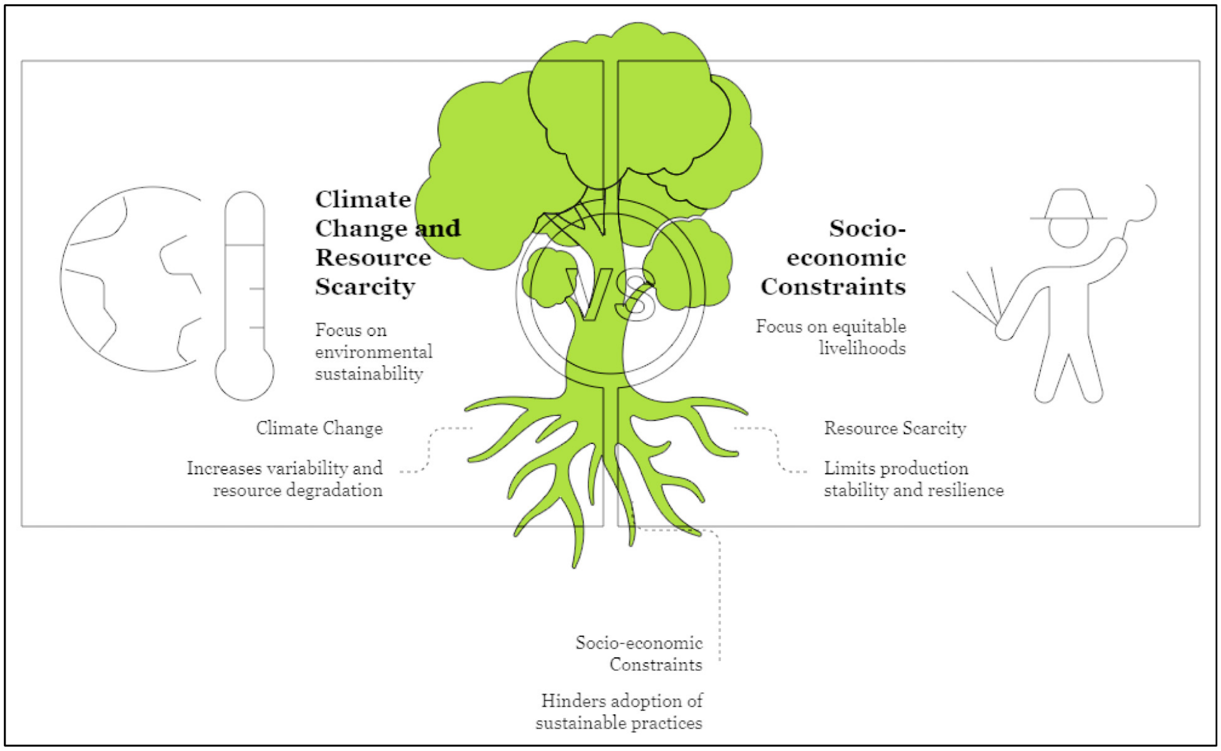

Fig. 1. Conceptual framework of resilient farming systems for green agriculture

Resilience-Enhancing Farming System Strategies

Resilient Farming Systems for Green Agriculture integrate diversification, resource-efficient practices, and climate-responsive technologies to enhance productivity while safeguarding natural resources. By combining conservation agriculture, integrated nutrient and water management, efficient irrigation, and rainwater harvesting, these systems strengthen soil health, improve water-use efficiency, and stabilize farm incomes (Fig. 2). The strategic use of digital tools and climate-

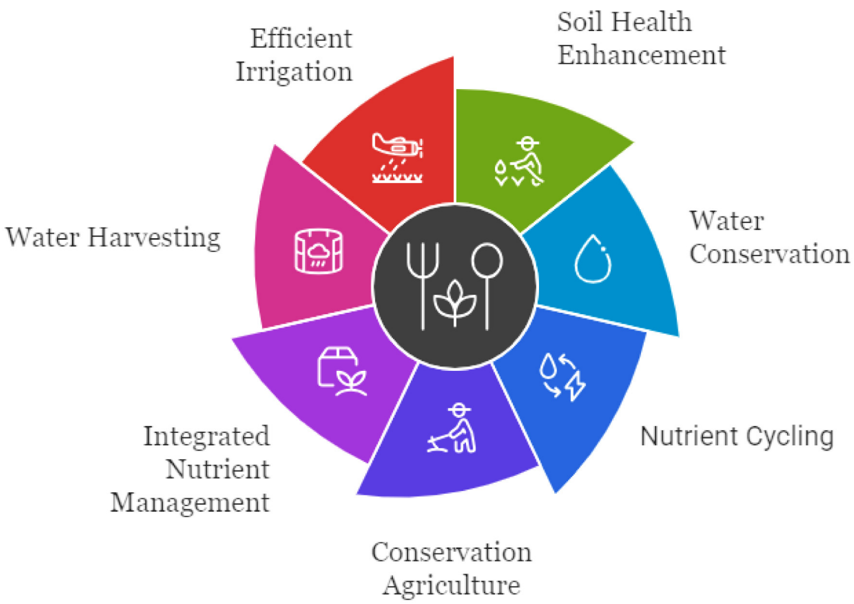

Fig. 2. Component of Resilient Farming System

adaptive innovations further enhances the capacity of farming systems to absorb shocks, adapt to variability, and sustain long-term agricultural resilience.

Diversified Cropping Systems

Crop rotations, intercropping, and agroforestry enhance resilience by improving nutrient cycling, suppressing pests, and spreading climatic risk. Long-term experimental evidence demonstrates that diversification with maize, millets, oilseeds, pulses, horticulture crops, forage crops etc improves yield stability and water productivity, even when mean yields are comparable to monocultures. Crop rotation reported to significantly improve soil structure and organic matter content while enhancing nutrient cycling (Musawi *et al*. 2025). Their study demonstrated that the inclusion of legumes in crop rotations increased soil organic carbon by up to 18% compared with monoculture systems. In addition, diversified rotations contributed to the mitigation of greenhouse gas emissions by enhancing carbon sequestration and reducing nutrient leaching and pesticide runoff, thereby supporting more sustainable and climate-resilient agroecosystems.

Conservation Agriculture

Conservation agriculture enhances soil structure, soil moisture retention, and biological activity. Although short-term yield penalties may be observed in certain agro-ecological conditions, long-term benefits include reduced soil erosion, improved water infiltration, and enhanced soil carbon sequestration. Hossain *et al*. (2021) reported that conservation agriculture represents a next-generation, climate-resilient crop management approach that significantly contributes to food security while simultaneously improving environmental health.

Integrated Farming Systems (IFS)

Integrated Farming Systems represent a cornerstone of resilient and green agriculture by synergistically combining crops, livestock, fisheries, and trees. Such integration facilitates internal recycling of nutrients and energy, reduces dependence on external inputs, and generates diversified income streams. Systems-based research indicates that IFS enhance resilience by buffering farm households against climatic and market shocks while improving water-use efficiency, soil health, and environmental quality (Mishra *et al*., 2023). Promotion of organic and natural farming in a system approach would contribute to building system resilience and sustainable production.

Climate-Smart Agriculture

Climate-smart agriculture provides an overarching framework for operationalizing resilience by simultaneously addressing productivity, adaptation, and mitigation objectives. Resilience assessment within CSA has increasingly shifted toward system-level indicators, such as yield stability, emission intensity, and water footprints. Practices including cover cropping, residue mulching, no-till farming, bed planting, intercropping and crop rotation enhance soil carbon storage and adaptive capacity (Abhilash *et al*., 2021).

Agroforestry

Agroforestry systems integrate trees with crops and/or livestock, enhancing structural and functional diversity. These systems contribute to carbon sequestration, microclimate regulation, biodiversity conservation, and livelihood resilience, making them integral to climate-adaptive agricultural landscapes (van Noordwijk *et al*., 2021).

Water Stewardship and Digital Innovations

Efficient water management is a cornerstone of resilient farming systems, particularly under increasing climate variability and water scarcity. Micro-irrigation technologies, including drip and sprinkler systems, substantially reduce conveyance and evaporative losses, and their integration with rainwater harvesting structures—such as farm ponds, check dams, and rooftop harvesting systems—significantly enhances on-farm water security. Within this framework, green agriculture farm tools play a pivotal role in integrating crop diversification, advanced technologies, and climate adaptation strategies. Resource-efficient tools, including precision irrigation systems, soil moisture sensors, and automated weather-based advisories, optimize water and nutrient use while minimizing environmental footprints. Climate-smart machinery, such as solar-powered farm implements and conservation agriculture equipment (e.g., zero-till seeders and residue management tools), supports diversified cropping systems, improves soil structure and health, enhances carbon sequestration, and increases energy-use efficiency. Furthermore, digital agriculture tools—remote sensing, GIS-based decision support systems, and mobile-enabled farm advisory platforms—strengthen farmers' adaptive capacity by enabling timely, data-driven responses to climate variability and extreme weather events. Advances in digital water management further reinforce water stewardship, as sensor-based soil moisture monitoring, precision irrigation scheduling, and crop water requirement models ensure irrigation is applied only when and where required, thereby improving water productivity. Emerging technologies such as the Internet of Underground Things (IoUT) facilitate real-time monitoring of root-zone dynamics, enabling site-specific irrigation decisions and enhancing the resilience and sustainability of agricultural production systems (Vuran *et al*., 2018). Integration of sensor networks with crop growth and hydrological models facilitates scenario analysis, early warning systems, and risk-informed decision-making. Machine learning applications are increasingly employed for yield forecasting and stress diagnostics. However, challenges related to data availability, algorithm transparency, and institutional capacity continue to constrain widespread adoption, particularly in smallholder systems.

Research Gaps and Policy Implications

Despite growing evidence of benefits, large-scale adoption of resilient farming systems remains limited. The main gaps include inadequate long-term systems research, insufficient integration of socio-economic dimensions, and weak alignment between technological innovation and institutional support. Policies must therefore prioritize investments in participatory research, digital infrastructure, inclusive extension systems, and capacity building to enable equitable and scalable transitions.

Conclusions

Resilient farming systems constitute the operational foundation of green agriculture by integrating diversification, ecological processes, and technological innovation. In the face of climate change and resource constraints, transitioning toward such systems is no longer optional but essential. A systems-oriented approach—linking biophysical resilience with socio-economic adaptability and supportive policy frameworks—is critical for achieving sustainable and climate-resilient agricultural futures in India and beyond.

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National Seminar on Innovations in Agrophysics for Green Agriculture
22-24 January 2026 at ICAR-IIWM, Bhubaneswar

Integrated Farming Systems for Green and Sustainable Agriculture

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ABSTRACT

Integrated farming systems (IFS) and green agriculture represent transformative approaches to sustainable food production in the face of climate change, environmental degradation, and growing food security challenges. IFS integrate multiple farm enterprises crops, livestock, aquaculture, horticulture, and agroforestry, creating synergistic relationships that enhance productivity, profitability, and environmental sustainability. Evidence demonstrate that IFS offers substantial environmental benefits including greenhouse gas reduction, carbon sequestration, improved soil health, enhanced biodiversity, and efficient nutrient cycling, while simultaneously delivering economic advantages through increased productivity, profitability, and resource efficiency. These systems are particularly beneficial for small and marginal farmers, providing pathways to food security, livelihood improvement, and climate resilience. IFS adoption increases farm net profit by approximately 660 USD annually while improving soil health, biodiversity, and climate resilience. Government initiatives like the All India Coordinated Research Project on IFS demonstrate robust policy commitment. Key findings indicate that successful implementation requires supportive policies, technical knowledge transfer, and context-specific adaptation to local agroecological conditions.

Key words: Integrated Farming Systems, Green Agriculture, Sustainable Development, Food Security, Climate Resilience, India

Introduction

Modern agriculture faces unprecedented challenges in meeting the food demands of a growing global population while addressing environmental sustainability, climate change, and resource constraints. Conventional agricultural intensification, characterized by monoculture systems and heavy reliance on synthetic inputs, has achieved remarkable productivity gains but at significant environmental costs including soil degradation, biodiversity loss, water pollution, and greenhouse gas emissions (Kumar *et al.,* 2023; Swarnam *et al.,* 2024). In response to these challenges, integrated farming systems have emerged as a holistic alternative that seeks to reconcile agricultural productivity with environmental stewardship and socioeconomic viability (Shanmugam *et al.,* 2024; Marchão *et al.,* 2024).

Integrated farming systems represent a paradigm shift from simplified, specialized agriculture toward diversified, synergistic production systems that combine multiple agricultural components-typically crops, livestock, and sometimes agroforestry-within a single farm or landscape (Gill *et al.,* 2009; Kumar *et al.*, 2023; Meena *et al.,* 2024). These systems are designed to maximize resource use efficiency, minimize external inputs, enhance ecosystem services, and improve farm resilience through functional complementarities among different enterprises (Behera and France, 2016; Bahadur *et al.*2024; Bonaudo *et al.,* 2014). The integration of diverse components creates opportunities for nutrient recycling, waste valorisation, risk diversification, and multiple income streams, making farms more productive, economically viable, and environmentally sustainable.

Defining Integrated Farming Systems

Integrated farming systems are characterized by the deliberate combination and spatial-temporal arrangement of multiple agricultural components within a farm, designed to create synergistic interactions that enhance overall system performance (Bhagat *et al.,* 2024; Gill *et al.,* 2009). The fundamental principle underlying IFS is that the whole system produces more value in terms of productivity, profitability, and ecosystem services than the sum of its individual components operating independently (Taube *et al.,* 2023; Thakur *et al.,* 2025). This emergent property arises from functional complementarities such as nutrient cycling between crops and livestock, pest regulation through biodiversity, and efficient use of farm resources including land, labor, and capital (Bahadur *et al.,* 2024; Bhati *et al.,* 2024).

Agroecological Principles

Bonaudo *et al.* (2014) identified key agroecological principles for redesigning integrated crop-livestock systems, including: (1) enhancing recycling of biomass and nutrients; (2) strengthening the immune system of agricultural systems through diversification; (3) providing favourable soil conditions for plant growth; (4) minimizing losses of energy, water, nutrients, and genetic resources; and (5) diversifying species and genetic resources in the agroecosystem over time and space. These principles translate into practical design features such as using livestock manure to fertilize crops, incorporating legumes for biological nitrogen fixation, utilizing crop residues as animal feed, implementing rotational grazing to improve pasture and soil quality, and maintaining habitat diversity to support beneficial organisms (Paula *et al.*, 2017; Puech *et al.*, 2023; Selvan *et al.*, 2023).

Systems Approach and Circular Economy

The circular economy concept provides another important framework for integrated farming, emphasizing the reprocessing and reuse of agricultural residues to create closed-loop systems that minimize waste and external inputs. Selvan *et al.* (2023) demonstrated how integrated organic farming systems exemplify circular economy principles through nutrient recycling, organic waste valorization, and efficient resource use. This approach reduces environmental impacts while improving economic efficiency by converting potential waste streams into valuable inputs for other farm enterprises (Santos *et al.*, 2024; Palsaniya *et al.*, 2022).

Crop-Livestock Integration

Crop-livestock integration represents the most common and widely studied form of integrated farming, combining crop production with animal husbandry in mutually beneficial arrangements (Shanmugam *et al.*, 2024; Delandmeter *et al.*, 2023). The fundamental synergies in crop-livestock systems include: livestock providing manure for crop fertilization, crops providing feed and fodder for animals, livestock utilizing crop residues that would otherwise be wasted, and animals contributing to weed control and soil improvement through grazing. These interactions create opportunities for nutrient cycling, reduced input costs, diversified income sources, and improved risk management. Shanmugam *et al.* (2024) emphasized that crop-livestock integration offers a strategy to achieve synergy between agricultural production, nutritional security, and environmental sustainability. Their analysis showed that integrated systems enhance nutrient use efficiency, reduce greenhouse gas emissions per unit of product, improve soil organic matter, and provide diversified nutritious food including both plant and animal products.

Crop-Livestock-Agroforestry Systems

The integration of agroforestry components with crops and livestock creates even more complex and potentially beneficial systems (Marchão *et al.*, 2024; Santos *et al.*, 2024). Trees provide additional products (timber, fruit, fodder), ecosystem services (shade, windbreaks, carbon sequestration, biodiversity habitat), and production stability (Palsaniya *et al.*, 2022; Maracaípe *et al.*, 2025). Such systems deliver improved soil health through increased organic matter inputs, enhanced nutrient cycling, better water infiltration, and reduced erosion compared to simpler crop or livestock systems. The tree component plays a crucial role in these benefits through deep rooting, continuous organic matter inputs, and microclimate modification (Palsaniya *et al.*, 2022; Maracaípe *et al.*, 2025).

Design Considerations and Optimization

Designing effective integrated farming systems requires careful consideration of multiple factors including component selection, spatial arrangement, temporal sequencing, resource allocation, and management practices (Kumar *et al.*, 2023; Bahadur *et al.*, 2024; Palsaniya *et al.*, 2021). Key design principles include: (1) selecting compatible components that complement rather than compete with each other; (2) arranging components spatially to facilitate beneficial interactions and efficient resource use; (3) sequencing activities temporally to maintain year-round productivity and labor distribution; (4) sizing components appropriately relative to available resources and market demand; and (5) implementing management practices that enhance synergies while minimizing conflicts (Lafontaine *et al.*, 2014).

Environmental Benefits and Ecosystem Services

Integrated farming systems deliver substantial benefits for soil health through multiple mechanisms including increased organic matter inputs, enhanced biological activity, improved nutrient cycling, and reduced erosion (Kumar *et al.*, 2013; Marchão *et al.*, 2009). The improvement in soil organic matter is particularly important for long-term soil fertility and productivity. Santos *et al.* (2018) found that IFS systems in the Brazilian Cerrado increased soil organic carbon stocks by 20-40% compared to conventional systems, with benefits extending to deeper soil layers. This carbon accumulation improves soil water-holding capacity, nutrient retention, and resilience to drought and degradation (Marchão *et al.*, 2009). Enhanced soil biological activity in integrated systems contributes to nutrient mineralization, disease suppression, and soil structure formation (Bhagat *et al.*, 2017; Taube *et al.*, 2014). Nutrient cycling efficiency is markedly improved in integrated systems through the recycling of organic materials between components (Kumar *et al.*, 2025; Delandmeter *et al.*, 2019; Lal *et al.*, 2020).

Biodiversity Conservation

Integrated farming systems support greater biodiversity than simplified monoculture systems through habitat diversification, reduced pesticide use, and maintenance of landscape heterogeneity

(Bhagat *et al.*, 2024; Urbaite, 2025). The presence of multiple crops, pastures, trees, and other vegetation creates diverse habitats for beneficial organisms including pollinators, natural enemies of pests, and soil organisms (Ansari *et al.*, 2024; Dushyant *et al.*, 2024). The biodiversity benefits extend beyond the farm level to landscape-scale conservation (Palsaniya *et al.*, 2022; Santos *et al.*, 2024). The reduced use of synthetic pesticides in integrated systems, facilitated by biological pest control and crop diversification, further benefits biodiversity (Babu *et al.*, 2023; Selvan *et al.*, 2023). This biodiversity enhancement has functional value for agricultural production through improved pollination, pest regulation, and nutrient cycling.

Water Management and Quality

Enhanced soil organic matter and structure improve water infiltration and retention, reducing runoff and increasing drought resilience (Marchão *et al.*, 2024). Diverse vegetation cover, particularly in systems with forestry components, reduces soil erosion and associated sediment pollution of water bodies (Maracaípe *et al.*, 2025). The efficient nutrient cycling in integrated systems reduces nutrient losses to groundwater and surface water, addressing a major environmental problem associated with intensive agriculture. In water-scarce regions, integrated systems offer opportunities for more efficient water allocation across enterprises (Swarnam *et al.*, 2024; Raghavendra *et al.*, 2024).

Greenhouse Gas Mitigation

Palsaniya *et al.* (2022) demonstrated that integrated crop and livestock systems increase both climate change adaptation and mitigation capacities through diversification, improved resource efficiency, and enhanced carbon sequestration. Their analysis showed that integration can reduce greenhouse gas emissions intensity by 20-40% compared to specialized systems while simultaneously improving system resilience to climate variability. The climate benefits of integrated systems are enhanced by reduced dependence on fossil fuel-based inputs including synthetic fertilizers, pesticides, and mechanization (Dhaliwal *et al.*, 2022; Selvan *et al.*, 2023). The efficient nutrient cycling through organic matter recycling reduces nitrous oxide emissions associated with synthetic nitrogen fertilizer use.

Economic Performance and Livelihood Impacts

Several studies have documented the economic advantages of integrated systems through empirical analysis (Kumar and Singh, 2023; Raghavendra *et al.*, 2024; Henrique *et al.*, 2015). However, economic performance varies with system design, management intensity, market access, and policy support (Leterme *et al.*, 2019). The synergies among components enable higher total productivity per unit of land, labor, and capital compared to specialized systems (Meena *et al.*, 2024; Bahadur *et al.*, 2024). The diversification of products provides multiple income streams, reducing economic risk and improving cash flow throughout the year (Raghavendra *et al.*, 2025; Palsaniya *et al.*, 2021). The economic viability of integrated systems is enhanced when environmental benefits are recognized and rewarded through payments for ecosystem services or premium markets (Lafontaine *et al.*, 2014).

Food and Nutritional Security

The diversification of production provides a more varied and nutritious diet including cereals, pulses, vegetables, fruits, milk, eggs, and meat (Palsaniya *et al.*, 2021). Kumar *et al.* (2025) highlighted that crop-livestock integration offers a strategy to achieve nutritional security by providing both plant and animal-source foods rich in essential nutrients. The year-round production from multiple components improves food availability and access throughout the year, reducing seasonal food insecurity (Kumar *et al.*, 2022; Palsaniya *et al.*, 2022). For subsistence-oriented smallholders, integrated systems provide direct food production for household consumption while generating marketable surpluses for income (Thakur *et al.*, 2025). The systems provide multiple pathways to food security: direct food production, income generation, employment opportunities, and enhanced resilience to shocks (Kumar *et al.*, 2022). The nutritional benefits are enhanced when systems include diverse crops, livestock, and horticultural components that provide micronutrient-rich foods (Shanmugam *et al.*, 2024; Selvan *et al.*, 2023).

Employment and Livelihoods

The diversification of activities distributes labour demand more evenly throughout the year, reducing seasonal unemployment and improving labor productivity (Thakur *et al.*, 2025). The livelihood benefits extend beyond income and employment to include improved quality of life, social capital, and community resilience (Kumar and Singh, 2023; Palsaniya *et al.*, 2022). The systems provide opportunities for women and youth engagement in various enterprises, contributing to social inclusion and empowerment (Meena *et al.*, 2024; Shyam *et al.*, 2023). Kumar and Singh (2023) demonstrated that integrated crop-livestock systems improve livelihood security for small and medium farmers through risk diversification, enhanced productivity, and improved sustainability. The systems build adaptive capacity by providing multiple livelihood options and reducing dependence on single enterprises vulnerable to climate or market shocks (Selbonne *et al.*, 2022; Palsaniya *et al.*, 2021).

Climate Change Adaptation and Mitigation

The diversification of enterprises provides insurance against climate-related production failures, as different components respond differently to climate variability (Shanmugam *et al.*, 2024). The soil health improvements in integrated systems, particularly increased organic matter and improved structure, enhance resilience to drought, flooding, and temperature extremes (Bhagat *et al.*, 2024; Marchão *et al.*, 2024). Better soil water-holding capacity buffers against drought stress, while improved infiltration reduces waterlogging and erosion during heavy rainfall (Paula *et al.*, 2017; Kumar *et al.*, 2023). Swarnam *et al.* (2024) emphasized that climate-smart crop-livestock integration is particularly important for vulnerable regions such as tropical islands, where climate change impacts are severe and adaptation options limited. The systems provide farmers with multiple options for adjusting management in response to climate variability, including changing crop-livestock ratios, adjusting planting dates, and modifying grazing strategies (Kumar *et al.*, 2022; Selbonne *et al.*, 2022).

Mitigation Potential

Integrated crop-livestock-forestry systems offer particularly strong mitigation benefits through soil carbon accumulation, biomass carbon storage in trees, and reduced emissions intensity (Marchão *et al.*, 2024; Paula *et al.*, 2017; Kumar *et al.*, 2023). Santos *et al.* (2024) documented that agroforestry systems in the Brazilian Cerrado can sequester 2-4 tons of carbon per hectare per year in soil and biomass, potentially achieving carbon neutrality or net carbon removal. Kumar and Singh (2023) demonstrated the long-term impact of integrated crop-livestock systems on carbon emission reduction and sustainability. However, realizing the full mitigation potential requires careful management to optimize carbon sequestration while minimizing emissions from livestock and soil disturbance.

Climate-Smart Agriculture

The climate-smart attributes of integrated systems are enhanced by their flexibility and adaptability to local conditions (Shyam *et al.*, 2023). Farmers can adjust system configuration and management practices in response to changing climate conditions, market opportunities, and policy incentives (Palsaniya *et al.*, 2021*;* Lafontaine *et al.*, 2014). However, scaling up climate-smart integrated farming requires supportive policies, technical assistance, and investment in infrastructure and knowledge systems (Selbonne *et al.*, 2022*;* Raghavendra *et al.*, 2024). The integration of traditional knowledge with modern science can enhance the climate-smartness of systems while ensuring social acceptability and cultural appropriateness.

Implementation Challenges and Enabling Factors

The successful implementation of integrated farming systems requires substantial technical knowledge and management skills, presenting a significant barrier for many farmers (Kumar *et al.*, 2022*;* Babu *et al.*, 2023*;* Selvan *et al.*, 2023). The complexity of managing multiple interacting components demands understanding of crop-livestock interactions, nutrient cycling, pest and disease management, and systems-level optimization.

Selvan *et al.* (2023) noted that inadequacy of proficiency, financial resources, and technical expertise are major constraints to implementing integrated organic farming systems. Addressing these knowledge barriers requires investment in farmer education, extension capacity building, and participatory research to develop and adapt practices to local conditions (Raghavendra *et al.*, 2025*;* Dhaliwal *et al.*, 2022). Farmer-to-farmer learning, demonstration farms, and participatory research can facilitate knowledge transfer and reduce transition risks (Alhameid *et al.*, 2017).

Economic and Market Constraints

Economic and market constraints present significant barriers to adoption of integrated farming systems (Leterme *et al.*, 2019; Selvan *et al.*, 2023). The initial investment required for establishing integrated systems, including infrastructure for livestock housing, fencing, water systems, and equipment can be prohibitive for resource-poor farmers (Meena *et al.*, 2024; Palsaniya *et al.*, 2021). Market access and value chains for diverse products from integrated systems are often underdeveloped, limiting economic returns (Lafontaine *et al.*, 2014). Specialized value chains favor large-scale, uniform production, disadvantaging diversified small-scale producers. Selvan *et al.* (2023) noted that market infrastructure and premium pricing for sustainably produced products are needed to realize the economic potential of integrated organic farming systems. IFS can increase net farm profit by approximately 660 USD (approx. INR 55,000) per year for smallholders (Paramesh *et al.*, 2022). Payments for environmental services, organic certification premiums, and support for infrastructure development can improve economic attractiveness.

Policy and Institutional Support

Supportive policies and institutions are critical enabling factors for scaling up integrated farming systems (Selbonne *et al.*, 2022; Leterme *et al.*, 2019). Policy reform is needed to level the playing field by removing perverse incentives for specialization, providing support for diversification, and rewarding environmental stewardship (Taube *et al.*, 2023). Raghavendra *et al.* (2024) emphasized the importance of participatory policy development that engages farmers and other stakeholders in designing supportive frameworks. Institutional innovations including farmer cooperatives, multi-stakeholder platforms, and knowledge networks can facilitate adoption of integrated farming (Babu *et al.*, 2023; Palsaniya *et al.*, 2021). These institutions provide mechanisms for collective action, knowledge sharing, market access, and advocacy for supportive policies.

Regional Perspectives and Case Studies from India

In India, integrated farming systems have been promoted as a strategy for sustainable development of small and marginal farmers (Ravisankar *et al.*, 2007; Kumar *et al.*, 2025; Shyam *et al.*, 2023; Kumar *et al.*, 2022; Thakur *et al.*, 2025). Swarnam *et al.* (2024) documented climate-smart crop-livestock integration in humid tropical islands, demonstrating substantial benefits for productivity, sustainability, and climate resilience. Kumar *et al.* (2022) emphasized that integrated systems are particularly important for small and marginal farmers in India, providing pathways to food security, income improvement, and sustainable livelihoods. Palsaniya *et al.* (2021) documented an integrated multi-enterprise system in semi-arid tropics of central India, demonstrating sustained livelihood benefits, efficient energy use, and effective resource recycling.

Future Directions and Research Needs

Despite substantial progress in understanding integrated farming systems, significant knowledge gaps remain that require further research (Babu *et al.*, 2023; Dhaliwal *et al.*, 2022; Selbonne *et al.*, 2022). Key research priorities include: (1) quantifying long-term sustainability outcomes across diverse contexts; (2) optimizing system designs for specific agroecological and socioeconomic conditions; (3) understanding mechanisms and management of component interactions; (4) developing decision support tools for farmers and advisors; and (5) evaluating scaling pathways and policy options. Methodological advances are needed to better assess integrated systems, including systems-level indicators, life cycle assessment approaches, and participatory evaluation methods that capture farmer perspectives and local knowledge (Raghavendra *et al.*, 2024; Puech *et al.*, 2019). Research should also address the social and institutional dimensions of integrated farming, including knowledge systems, organizational innovations, and policy frameworks (Babu *et al.*, 2023; Palsaniya *et al.*, 2022; Schut *et al.*, 2021).

Technology and Innovation

Precision agriculture technologies including sensors, drones, and data analytics, digital platforms, biotechnology and breeding innovations can increase IFS efficiency and yield. However, technology development should be guided by agroecological principles and farmer needs rather than purely technical considerations. Selvan *et al.* (2023) emphasized that circular economy approaches in agriculture require innovations in waste valorisation, nutrient recycling technologies, and market mechanisms for sustainably produced products.

Scaling and Policy Development

Scaling strategies should be context-specific, recognizing diverse farmer circumstances, agroecological conditions, and institutional contexts (Raghavendra *et al.*, 2025; Leterme *et al.*, 2019).

Policy development should be evidence-based, drawing on research and practical experience, and participatory, engaging farmers and other stakeholders in design and implementation (Alhameid *et al.*, 2017). International cooperation and knowledge exchange can facilitate policy learning and adaptation of successful approaches across contexts.

Conclusion

Integrated farming systems represent a transformative approach to sustainable agriculture that addresses multiple challenges including food security, environmental degradation, climate change, and rural livelihoods. These systems enhance productivity and profitability while providing critical ecosystem services including soil health improvement, biodiversity conservation, water quality protection, and climate change mitigation. The success of integrated farming systems is grounded in agroecological principles that emphasize working with natural processes, enhancing beneficial interactions among components, and optimizing whole-system performance rather than individual components.

Realizing the full potential of integrated farming requires addressing significant barriers including knowledge gaps, economic constraints, and policy frameworks that favour specialization. Successful scaling up demands investment in farmer education and technical support, development of appropriate market infrastructure and value chains, and policy reforms that recognize and reward the multiple benefits of integrated systems. The transition from specialized to integrated farming involves learning costs and risks that require supportive institutions and policies to manage.

Regional experiences from tropical smallholder systems demonstrate that integrated farming can be successfully implemented across diverse contexts but requires context-specific adaptation of principles and practices. Continued research is needed to optimize system designs, understand long-term sustainability outcomes, and develop effective scaling strategies. Integrated farming systems offer a viable and attractive pathway toward sustainable agriculture that can meet food security needs while protecting environmental resources and supporting rural livelihoods.

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Soil Physics-based Soil and Water Conservation Strategies for Green Agriculture

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ABSTRACT

Soil physics and associated soil properties play a central role in regulating the soil–plant–atmosphere continuum by controlling the storage and movement of water, air, and heat within the soil profile. Soil physical properties such as soil texture, structure, bulk density, porosity, and aggregate stability determine soil water retention, infiltration, hydraulic conductivity, drainage, and aeration, thereby influencing plant-available water and oxygen supply to roots and soil biota. Land degradation processes such as erosion, salinity, compaction etc disrupt soil physical properties, causing severe erosion, salt encrustation, hindering seedling emergence, reduced water use efficiency, diminishing crop productivity and ecosystem functions. In this context, soil and water conservation strategies include agronomic and engineering approaches such as conservational agriculture, cover crops, mulching, amendments, check dams, contour trenches, gully plugs etc effectively combat erosion, improve water retention and foster better soil health. Integrating traditional soil conservation methods with machine learning an AL will improve the physical properties of soil by enabling real time, data driven and targeted interventions for achieving the goals of green agriculture.

Key words: Soil erosion, Conservation practices, Crop productivity, Soil physical properties

Introduction

Agrophysics aims to enhance agricultural productivity by improving soil's physical properties, conserving natural resources and minimising environmental degradation, focusing on green agriculture. Soil and water conservation practices, in this context, play a crucial role for India and other Asian countries, which are vulnerable to a changing climate scenario, continuous land degradation pressure and land intensification (Lal, 2015). Soil physical properties or agrophysics principles provide a comprehensive understanding of basic soil processes that govern water transmission, pore connectivity, structure stability, air and water balance, temperature fluctuations, which directly impact crop nutrient-water uptake, root growth and energy exchange in the soil-plant-atmosphere continuum (Bronick and Lal, 2005).

Soil physical properties such as bulk density, water holding capacity, compaction and structure are crucial for green agriculture. All these properties are directly influenced by adopted SWC measures. Various soil degradation processes such as erosion, salinity/ sodicity, compaction, crusting etc initiate in soil with deteriorating physical properties, leading to poor soil structure, lower water retention, surface sealing, restricted root development and limiting crop productivity (Dexter 2004). Therefore, the timely implementation of soil and water conservation (SWC) practices increases soil organic carbon, improves soil aggregation, enhances water retention and infiltration, and reduces bulk density and compaction.

Indian agroecosystem covering wide areas under rainfed system, dryland agriculture, coastal agriculture, tablelands, gully eroded and ravine system, command areas, arid ecosystem etc suffers from one or other physical constraints. According to the latest estimate by the Indian Council of Agricultural Research (ICAR) and National Academy of Agricultural Sciences (NAAS), out of a total geographical area of 328.73 million hectares, 120 million hectares (37 %) are affected by various degrees of land degradation (Department of Agriculture & Cooperation, Ministry of Agriculture, 2015). In India soil and land degradation is a major threat to food security. As per FAO (2015), primary factors of land degradation in India are water and wind erosion (94.9 Mha), soil acidity (17.9 Mha), sodic soils (3.7 Mha), saline soils (2.7 Mha), water logged soils (0.91 Mha), and minespoil- industrial waste (0.26 Mha). Therefore, location-specific, soil physics-based conservation strategies are necessary to address these challenges to sustain production and ecosystem services (Bandyopadhyay *et al*. 2009). Soil and water conservation measures such as conservation or reduced tillage, mulching, crop residue management, cover crops, contour bunding, check dams etc are effective in improving soil physical properties, consequently reducing runoff and erosion losses, increasing infiltration, enhancing aggregate stability, maintaining soil temperature and regulating soil moisture. However, with the increasing climate change scenario- extreme rainfall events, droughts, ground water depletion, there is a mounting need to integrate new advanced agrophysics tools with traditional SWC practices. The manuscript highlights the role of soil physics in supporting soil and water conservation for green agriculture, with special emphasis on emerging and innovative agrophysical tools and their prospects in Indian agroecosystems.

Soil physical properties governing soil and water conservation

Degraded lands are generally characterised by weak soil structure, high bulk density, poor aggregate stability, reduced infiltration rates, and low soil moisture. To address these challenges, soil and water conservation measures play an important role by reviving soil physical properties and re-establishing efficient water and energy balance in the soil system.

Agrophysics underlines the basic principle in understanding the role of soil physical properties such as bulk density, soil structure stability, soil moisture retention, energy exchange, soil temperature and aeration in the soil ecosystem. Green agriculture basically dependent on all these physical properties and their interaction with air, water and energy. The most important soil physical properties governing the soil and water conservation balance include rainfall–runoff dynamics, soil moisture retention/ storage pore size distribution, aggregation, hydraulic conductivity and drainage, bulk density, and soil temperature modifications.

1. Rainfall–Runoff dynamics

Land cover and land use have a specific influence on soil physical properties, which is directly related to soil erosion and runoff. The rainfall reaching the soil surface, either infiltrates into the soil or flow as surface runoff. The quantity of rainfall that infiltrates depends on soil structure, soil texture, aggregate formation, inherent soil moisture and organic matter content (Liu *et al*., 2011; Brady *et al*., 2017). Moreover, soil infiltrability is an important property for better understanding and managing of soil hydrological process, crop water uptake and translocation, irrigation, and soil erosion. In addition, during rainfall, soil infiltration capacity is also closely related to a many factors such as intensity and kinetic energy of rainfall, along with soil surface conditions. All these factors affect the infiltration rate by manipulating the surface seal or crust formation that results from physical compaction and physicochemical dispersion phenomena of raindrop impact (Assouline 2004). Soils with improved structure and stable aggregates permit higher infiltration rates, minimize surface runoff and soil erosion. Thus, maintaining good soil physical condition is essential for effective soil and water conservation.

2. Soil Moisture Storage and Plant Available Water

Soil moisture storage is the soil's ability to hold or retain water after drainage of excess water. Plant available water is easily extract by crops/ plants and stored in plants which is usually between field capacity and permanent wilting point. It is critical for managing both water and nutrient use efficiency of crops and therefore, necessary to investigate the soil properties influencing PAW. Soil texture, aggregate stability, bulk density, porosity distribution and organic carbon content are the key soil properties governing soil moisture storage and PAW. Water retention in soils at higher water potential values (>10kPa) is significantly influenced by macropores, BD, soil structure and texture (Beutler *et al.*, 2002). However, with depleting soil moisture content, adsorption becomes the major force, followed by other soil-specific properties such as organic matter, texture, mineralogy etc governs water retention (Hillel, 2004). Improved soil properties with the adoption of SWC increase soil moisture storage, reduce drought stress, improve crop resilience, and decrease irrigation requirements. Soil conservation practices such as reduced tillage, mulching etc improve soil structure help enhance water storage and reduce water loss.

3. Pore Size Distribution and Aggregation

The dual nature of soil structure is defined by the amalgamation of porosity and aggregate formation. It is well known fact that soil aggregates have a wider range of functions associated with various soil properties as compared to porosity. Soil aggregate stability increases soil cohesion force thereby reducing soil erosion. Additionally, well aggregated soils have better water holding capacity, reduced BD and higher pore space, making the soil more permeable, favouring erosion resistance in the long run (Ferreria *et al.*, 2023; Yang *et al.*, 2025). Soil aggregate stability is also known as the index for soil erodibility. Soil compaction by tillage operation on clay soils destroys soil structure, reduces porosity and increases bulk density. Soil and water conservation measures on the other hand increases pore volume and connectivity between soil colloids, reducing the expansion pressure of pores, thereby increasing the stability of soil aggregates. Well-aggregated soils have a balanced pore size distribution, which supports both water movement and water retention, thereby reducing soil erosion. The aggregate stability and pore space are strongly influenced by soil organic carbon. In agriculture, SOC is usually low due to regular tillage and biomass removal, leading to soil erosion and nutrient loss. Thus, SOC plays an essential and exceptional role influencing soil aggregate formation, and maintaining their stability. The stable aggregate formation and porosity are therefore critical for soil conservation and efficient water use (Lal, 2015).

4. Hydraulic Conductivity and Drainage

Hydraulic conductivity is the ability of the soil to transmit water through its pores. Soil erosion changes hydraulic conductivity and other soil physical properties, which in turn effect water infiltration, surface runoff and soil loss. Soils with sealed surfaces usually have low hydraulic conductivity and poor soil infiltrability. Hydraulic conductivity plays an indispensable role in transporting soil water and solutes and is regarded as an important parameter for hydrological modelling studies. Low hydraulic conductivity is common in compacted or sodic or sealed soils, which restrict drainage and cause surface ponding and runoff. Conservation approaches such as addition of organic amendments, mulching, residue retention, cover crops, crop rotation etc allows greater water movement and positively impact hydraulic conductivity (Li *et al*., 2021; Bagnall *et al*., 2022). Thus, maintaining soil structure and avoiding compaction are key to sustaining favourable hydraulic conductivity (FAO, 2011).

5. Soil Temperature Moderation Through Surface Cover

Soil physical properties such as texture, colour, moisture content significantly influence soil temperature. Application of soil surface mulch regulate soil temperature by altering energy absorption or reflecting thus reducing extreme fluctuation of soil temperature. Maintaining moderate soil temperature improves microbial activity, root growth, and soil structure formation. Surface mulching thus plays a crucial role in affecting absorption of solar radiation, heat dissipation and temperature regulation (Tang *et al*., 2023). This technique of SWC can effectively reduce soil temperature during extreme temperatures, thereby decreasing the soil moisture depletion. In addition, surface cover reduces evaporation losses, improves infiltration, and protects soil from raindrop impact, thereby reducing erosion (Lal, 2015).

Soil Physics-Based Conservation Strategies across Indian Agroecosystems

Soil physics-based conservation strategies, including conservation tillage, surface mulching and residue retention, mechanical interventions such as contour bunding, and soil amendments tailored to specific edaphic and hydrological conditions, aim to sustain soil physical quality, mitigate land degradation and enhance the climate resilience of farming systems.

a) Conservation Tillage, Mulching and Residue Retention for arable lands

Conservation tillage involves minimal soil disturbance, maintaining at least ~30 % soil surface cover by plant residues to reduce erosion and improve water infiltration and retention. Practices under this umbrella include no-till (NT), strip-till (ST) and mulch-till (MT), all of which moderate soil physical conditions by sustaining organic matter, aggregate stability and porosity compared to conventional tillage (CT) (Singh *et al*., 2025). Surface application of organic residues (crop stubble, straw), protects the soil surface from raindrop impact, reduces evaporation, moderates soil temperature fluctuations, and enhances moisture conservation, core soil physics functions (e.g., infiltration and evapotranspiration regulation).BBF shapes the soil into alternating raised beds and shallow furrows that facilitate drainage during intense monsoon rain, increase infiltration and conserve in-situ soil moisture during dry spells, collectively enhancing soil hydraulic properties in semi-arid contexts (Kumawat *et al*., 2025). Similarly, agro geotextile (AGT) not only provides surface protection against erosion, but reduces soil crusting and increases infiltration and soil moisture retention in Himalayan agroecosystem (Singh *et al*., 2019).

b) Erosion-Prone and Ravine Lands

Contour bunds with earthen embankments built along elevation contours intercept runoff, increase water residence time on slopes, and enhance infiltration, reducing soil loss. In Alfisols and other soils with gentle slopes, contour bunding consistently conserves both runoff and soil compared with graded bunds (Rao *et al*., 2022). Check dams and gully plugs are localized structures placed in waterways, drainage lines or gullies to slow concentrated flow, dissipate energy and trap sediments, effectively stabilizing degraded ravine and watershed areas. Combining contour bunding with vegetative measures such as grassed waterways or vegetative buffer strips also enhances soil stabilization via improved root binding and surface protection, improving soil physical integrity (Rao *et al*., 2022).

c) Canal Command Areas

In irrigated canal command systems, soil physics interventions optimise water distribution, reduce waterlogging, and maintain the dynamics of infiltration and percolation. Land levelling combined with adequate surface drainage, this prevents prolonged soil saturation, maintains aeration, and reduces conditions that otherwise contribute to increased bulk density and reduced infiltration capacity (FAO, 2025). Gypsum supplies Ca^{2+} that replaces Naz on exchange sites, reducing dispersion and structural breakdown, thereby improving soil aggregation, porosity and infiltration. Organic amendments (e.g., FYM and crop residues) further enhance soil structure and porosity through increased aggregate stability and biological activity (Zoca and Penn, 2017). Rashmi *et al*. (2024) showed that application of gypsum @ 2.5 t ha^{-1} with crop residue and farmyard manure (FYM) recorded a significant drop in exchangeable sodium percentage (ESP) (45–48 %), and bulk density (3–6 %) than that of the control. Raised bed planting is another SWC measure demonstrated in Indian field experiments, significantly reducing soil bulk density and increasing infiltration rates compared to conventional flat planting, indicating enhanced soil structure and physical quality under raised bed configurations (Sahu *et al*., 2024)

d) Arid and Coastal Ecosystems

Arid and coastal zones are challenged by wind erosion, low soil moisture availability, and intense evaporative demand, which degrade soil and constrain crop productivity. Surface mulches, including organic residues and biodegradable covers act as physical barriers that reduce direct soil exposure, limit evaporation, and improve soil moisture retention and temperature buffering, enhancing water availability for plants (Rao *et al*., 2022; Singh *et al*., 2024). In arid regions, in-situ moisture conservation practices such as BBF, ridges and furrows, and contour cultivation create micro-catchments that trap rainwater, promote infiltration, reduce runoff, and increase soil moisture storage, resulting in improved rainwater use efficiency and higher crop yields compared to flat sowing (Madhu and Jinger, 2025).

Role of agro-physics in restoration of degraded lands

Degraded lands are often characterised by poor soil physical properties such as lower aggregate stability, lower infiltration rates, compaction and crust formation. All these properties negatively affect crop performance, water use efficiency and resilience to climate variability.

a) Restoration of ravine landforms

Ravine and severely eroded lands classical form of physical soil degradation. Loss of topsoil, nutrients, and organic matter reduces soil aggregates and disrupts pore connectivity, causing runoff, soil loss and reduction in soil moisture storage. The SWC intervention, such as contour bunding, vegetative barriers, staggered contour trenches, peripheral bunds on gully heads etc modify slope geometry and rainfall–runoff relationships. These measures slow down the kinetic energy of flowing water, increase infiltration, and promote in sediment deposition. Soil and water conservation engineering measures provide short term erosion control, however long term improvement is achieved when soil physical properties improve to sustains vegetation and provide hydrological balance (Ali *et al*., 2020). Further, the plantation of grasses and trees further improves soil aggregation and structure through root biomass-induced binding and enhances microbial activity, causing reduced bulk density, improved porosity, and soil water holding capacity. Some of the grass and tree species for ravine stabilization includes *Vetiveria zizanioides*, *Acacia*, *Prosopis*, *Bamboo etc* (Singh *et al.,* 2015). Thus, with decreasing runoff, gully head advancement and sidewall erosion significantly slow, enabling geomorphic stabilisation of ravine systems. These physical improvements over time transform eroded landscapes into stable supporting agroforestry, pasture and other productive systems (Lal, 2015).

b) Restoration of salt-affected soils

Soil salinity is more evident in arid and semi-arid system, and is a different type of challenge where the interaction of salt, water in soil limits crop growth. Soil and water conservation measures such as efficient irrigation scheduling, leaching, subsurface drainage etc restore favourable soil water flow conditions, removing salts from the root zone. Organic amendment application further improves water-holding capacity, allowing better regulation of soil moisture and salt movement. Similarly, sodic soils and compacted soils have poor soil physical properties marked by severe structural degradation. These soils are commonly characterised by high exchange sodium percentage, causing dispersed soil colloids, and mechanical pressure increases soil bulk density, drastically reducing infiltration rate and hydraulic conductivity of soils. Application of inorganic amendments such as gypsum, phosphogypsum etc, organic amendments such as FYM, crop residue etc, reduced tillage operations, and biological techniques are conservation-based approaches in these soils. Gypsum and organic amendment application significantly reduced runoff (32%) and soil loss (54%) in salt-affected soils of western India (Rashmi *et al*., 2025). Thus, agrophysical management measures align with soil physical conditions with the goals of green agriculture (Brady and Weil, 2017).

c) Restoration of crusting-prone soils

Soil crust formation is a major physical constraint formed when raindrops on bare soil surface break down aggregates, forming a dense seal, restricting infiltration, increasing runoff and preventing seedling emergence. Soil and water conservation practices such as cover cropping, residue retention, reduced tillage, residue mulching, soil amendments etc act as physical buffers that protect soil aggregates and regulate soil temperature and evaporation. These surface modifications reduce the physical impact of raindrop, consequently, improve infiltration, enhance aggregation, conserve soil moisture, and create a favourable microclimate for seedling emergence and root growth (Lal, 2015).

Restoration of degraded lands aims to improve soil physical properties that support water holding capacity, stable aggregate formation, root growth, resistance to erosion and maintain ecosystem services. By integrating soil physical properties into restoration planning, practitioners can achieve resilient landscapes that support productivity and ecosystem health.

Emerging and Innovative Agrophysical Tools for Green Agriculture

Green agriculture emphasises the importance of soil physical properties, which support soil chemical and biological properties in improving crop production, sustaining soil health and food security. In this context, advanced tools of soil and water conservation measures are necessary to address location-specific challenges in an agroecosystem. Recent advances in agrophysics include nanotechnology for precision agriculture, a toolkit for analysing soil physical constraints, IoT-based technology, designing conservation measures, and monitoring their performance at multiple spatial and temporal scales. All these approaches transform the SWC from experience-based approaches to data-driven, precision-oriented management.

a) Remote Sensing and GIS-Based Assessment

Remote sensing techniques combined with Geographic Information Systems (GIS) have emerged as a powerful tool for large-scale assessment of soil physical degradation. Various satellite-derived indicators, such as vegetation indices, surface roughness, land surface temperature, and soil moisture, aid in the identification of erosion-susceptible areas, compaction zones, waterlogged areas, moisture-stressed, salt affected landscapes. Additionally, GIS-based watershed prioritisation further helps in targeting SWC measures such as check dams, contour bunds, trenches and gully plugs more effectively, thereby improving resource use efficiency. Advanced imaging and remote sensing, such as drones equipped with multispectral, hyperspectral and thermal camera can detect crop stress, nutrient deficiency, pest infestation, moisture stress etc resulting in precise interventions.

b) Soil–Water–Crop Simulation and Hydrological Models

Agrophysical advanced hydrological models and precision sensing provide insights into soil water balance, runoff generation, infiltration behaviour, and crop water uptake under different management scenarios. Currently, these models are moving towards AI-driven and real-time sensing simulations to optimise crop yield and reduce resource wastage. Watershed scale models such as SWAP (soil–water–atmosphere–plant) monitor the impact of minimum tillage, mulching, broad bed furrow system, raised bed, and drainage system before implementing on fields. These tools allow for precise, quantitative modelling, particularly useful in climate-vulnerable regions for predicting the impacts of rainfall variability on soil moisture dynamics and crop performance.

c) Sensors and Smart Monitoring Systems

Smart farming sensors such as IoT have enabled real-time monitoring of soil moisture, temperature, and bulk density changes. These data can be directly fed to models for refined predictions. Availability of low-cost soil moisture sensors and automated weather stations facilitate precision irrigation and moisture conservation, reducing water losses and enhancing water productivity. Advanced proximal soil sensors such as Ground penetrating radar, electromagnetic induction (EMI), electrical resistivity sensors, etc can directly measure soil moisture, conductivity and compaction in one go, without disturbing soil. These advanced tools supports continuous monitoring that helps assess the effectiveness of SWC interventions and supports adaptive management under changing field conditions.

d) Nanotechnology interventions

Nanotechnology utilises sensors that are self-diagnostic, wireless, and cost-effective sensors used for target-oriented results in agriculture. Nano sensors are real time monitoring system to detect pollutants, soil moisture, pH levels, and nutrient levels. Similarly, nano agrochemicals such as nano fertilisers and nano chemicals allow slow release of nutrients and active ingredients which significantly reduce the chemicals and minimize its runoff. Nanotechnology uses magnetic materials, ceramic and metal oxides to improve soil physical properties and enable higher nutrient uptake.

e) Digital Soil Mapping and Physical Soil Indicators

Digital mapping uses machine learning tools and sensors to generate high-resolution, spatial, and temporal data on soil properties. Machine learning and Algorithms are used to analyse massive datasets for predicting crop yields, identifying pests, and optimising resource use, with Random Forest and neural networks showing high accuracy. Thus, digital soil mapping integrates field observations, sensor data, and environmental covariates to generate spatially explicit information on soil physical properties. Soil physical indicators such as aggregate stability, available water capacity, bulk density, penetration resistance and hydraulic conductivity are increasingly used to evaluate soil physical health under conservation agriculture and restoration programs. These indicators provide a quantitative basis for assessing progress towards sustainable and green agricultural systems.

f) Integration with Nature-Based and Restoration Approaches

Nature based solution in innovative agrophysics tools involve agroforestry, vegetative barriers, organic amendments, bioengineering techniques, etc., for resource conservation, and minimising degradation. Understanding rhizosphere interactions, pore connectivity, soil structural recovery, and water retention through physical estimations strengthens restoration strategies in degraded lands such as ravines, sodic soils, and compacted tablelands.

Way Forward and Conclusions

Soil and water conservation strategies are powerful tools for facilitating green agriculture that will increase resource use efficiency, reduce environmental footprints and enhance sustainability. While traditional conservation practices remain relevant, their effectiveness can be significantly enhanced through the application of emerging agrophysical tools that enable precise diagnosis, planning, and monitoring. The transition from traditional, intensive farming to precision, technology-driven and restoration strategies can protect soil health and reduce carbon footprints. In this direction, the following strategies can effectively deliver the crucial role of agrophysics in green agriculture.

- Integrate soil physical indicators into routine soil health assessments and land-use planning.
- Machine learning and AI will promote sensor-based and remote sensing–supported decision systems for farmers and land managers.
- Develop region-specific agrophysical models tailored to Indian agroecosystems.
- Restorative and carbon farming will enhance carbon sequestration and support regenerative practices such as minimum tillage, nutrient use efficiency techniques etc
- Strengthen capacity building and interdisciplinary collaboration among soil physicists, agronomists, hydrologists, and extension professionals.

In conclusion, soil physics–based soil and water conservation offers a scientifically robust pathway for restoring degraded lands, improving resource use efficiency, and enhancing resilience to climate variability. Emerging agrophysical tools provide new opportunities to scale up conservation efforts and align them with the principles of green agriculture. Harnessing these tools effectively will be key to achieving sustainable agricultural productivity while safeguarding soil and water resources for future generations.

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Automating Impact-Based Agrometeorological Advisories under the GKMS Scheme in India

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Agrometeorological advisories play a critical role in bridging the gap between weather forecasts and farm-level decision-making. While weather forecasts provide information on atmospheric conditions, agromet advisories translate this information into crop-, location-, and stage-specific guidance that farmers can directly apply in their day-to-day operations. These advisories support informed decisions on sowing, irrigation, fertilizer application, pest and disease management, harvesting, and post-harvest operations. By aligning agricultural practices with prevailing and forecasted weather conditions, agromet advisories help reduce weather-induced risks, optimize resource use, and enhance crop productivity and profitability. In a climate-vulnerable country like India, where agriculture is highly sensitive to rainfall variability and extreme weather events, agrometeorological advisories are indispensable for building resilience and ensuring food security. India has one of the largest and most structured agrometeorological advisory frameworks in the world, implemented under the Gramin Krishi Mausam Sewa (GKMS) scheme of the India Meteorological Department (IMD). Under this system, district-level agromet advisories are prepared and disseminated through a network of Agrometeorological Field Units (AMFUs) and District Agromet Units (DAMUs) in collaboration with the Indian Council of Agricultural Research (ICAR), State Agricultural Universities, Indian Institute of Technologies (IITs), Non-Government Organisations etc. These advisories are issued twice (Tuesday and Friday) a week and are based on short- and medium-range weather forecasts, crop conditions, and local agronomic practices. Dissemination is carried out through multiple channels, including mobile applications such as Meghdoot and MAUSAM, SMS alerts, state IT platforms, print and electronic media, and extension networks. The system has significantly improved farmers' access to weather-based agricultural guidance and has demonstrated measurable economic benefits through improved farm decision-making. Despite its strengths, the current agromet advisory system relies considerably on manual interpretation and expert intervention, which can limit its scalability, timeliness, and customization. India's vast agro-climatic diversity, coupled with increasing weather variability, demands more frequent, hyper-local, and crop-specific advisories. Manual systems often struggle to process large volumes of real-time data from weather stations, satellites, and field sensors, leading to delays and generalized advisories. Furthermore, the growing demand for block-, village-, and even farm-level advisories necessitates automated systems capable of rapid data integration, analysis, and dissemination. Automation using advanced technologies such as artificial intelligence, machine learning, IoT-enabled sensors, and decision support systems can enhance the accuracy, consistency, and timeliness of agrometeorological advisories. Automated agromet advisory systems enable real-time processing of weather and crop data, generation of personalized advisories, and instant dissemination through digital platforms, thereby significantly strengthening the effectiveness of weather-based agricultural services.

The Seamless Weather Forecast System, developed by the IMD, plays a pivotal role in supporting agricultural decision-making through its comprehensive weather forecasts across multiple time scales. The system offers predictions that span from immediate nowcasts to long-term seasonal forecasts, helping farmers make well-informed decisions that enhance productivity and resilience in the face of climate change. The system operates across several forecast ranges, each catering to specific needs of farmers. For immediate threats, the Nowcast (0-3 hours) provides critical alerts for severe weather events like hail, frost, and thunderstorms, requiring urgent action. This short-term forecast allows farmers to take immediate protective measures, such as deploying anti-hail nets in orchards or activating emergency irrigation systems to safeguard crops. For example, a frost forecast can trigger protective irrigation for strawberry fields to prevent crop loss. The Short-range forecast (1-3 days) supports daily agricultural operations by providing updates on irrigation scheduling, fertigation timing, spray applications, and harvest planning. These forecasts allow farmers to optimize their activities based on the weather predictions. For instance, when rain is predicted within the next 24 hours, farmers might delay pesticide applications on tomatoes, minimizing waste and preventing runoff. The Medium-range forecast (4-7 days) extends further into predicting pest and disease pressures based on weather patterns and humidity trends. It helps farmers implement disease management strategies, such as initiating grape powdery mildew prevention protocols when a high humidity forecast is issued. Additionally, it guides optimal timing for nursery operations and vegetable transplanting schedules, allowing farmers to plan with a better understanding of the upcoming weather. Finally, the Long-range/Seasonal forecast, which covers weeks to months, aids in strategic agricultural planning by providing insights into crop selection, varietal choices, and water budgeting decisions. For example, monsoon forecasts can guide banana planting schedules, predict chilling hours for apple crops, and help in adjusting mango flowering times to optimize yields. By offering these multi-time scale predictions, the Seamless Weather Forecast System enables farmers to make precise, timely decisions that not only reduce risks but also improve resource

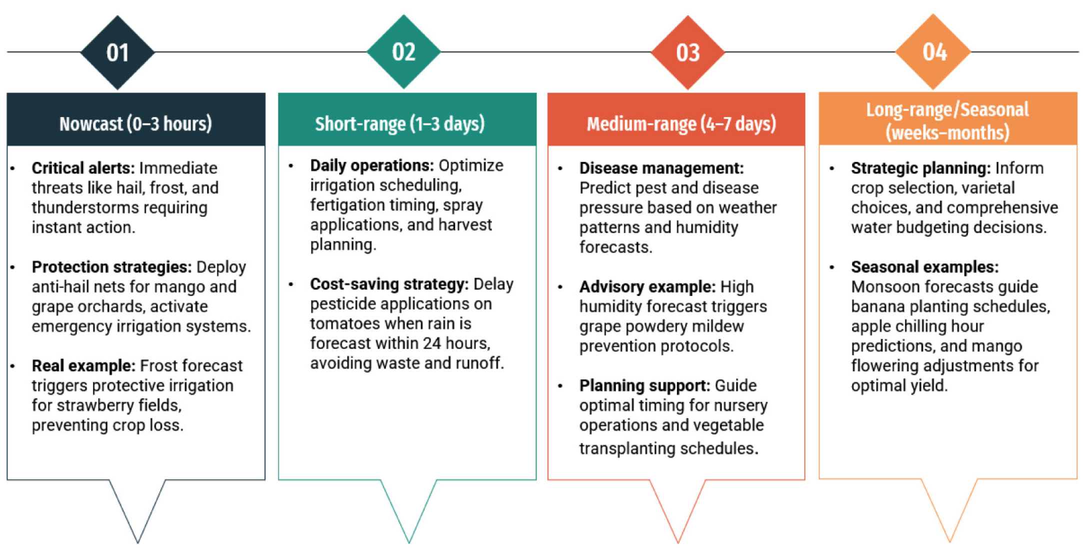

Fig. 1. IMD's Seamless Weather Forecast System: multi-time scale forecasts translating from nowcast to seasonal outlooks into actionable agricultural advisories

efficiency and productivity. Together, these forecasts offer a holistic approach to agricultural planning, empowering farmers with the tools to navigate the complexities of weather variability and climate change, ultimately ensuring more sustainable and resilient agricultural practices.

The comprehensive observational network of the IMD, encompassing surface observations, Agro-AWS, upper-air measurements, radars, and satellite-based remote sensing, provides a strong foundation for the future automation of agrometeorological advisories in India. At present, agromet advisories are largely prepared through expert interpretation of weather forecasts and crop conditions; however, the availability of dense, high-frequency, and multi-parameter observations offers significant potential to transition towards more automated and data-driven advisory systems. Automatic Weather Stations (AWS) generate continuous observations of temperature, rainfall, humidity, wind, and pressure, enabling real-time monitoring of evolving weather conditions. The Agro-Automatic Weather Stations (Agro-AWS), as a specialized component of IMD's observational network, further enhance this capability by additionally measuring soil moisture and soil temperature at multiple depths (10, 30, 70, and 100 cm). These observations provide objective information on root-zone soil water availability and thermal regimes, which are essential inputs for automating irrigation scheduling, crop stress assessment, and stage-specific advisories. Upper-air observations improve the skill of numerical weather prediction models across short-, medium-, and extended-range time scales, while satellite observations offer spatially continuous information on rainfall distribution, land surface conditions, vegetation health, and extreme weather systems. The integration of these diverse observations within data assimilation frameworks and decision support systems can enable rule-based, model-driven, and AI-assisted translation of weather and soil information into crop- and location-specific advisories. Thus, IMD's robust observational network serves as a critical enabler for progressively moving from predominantly manual agromet advisory preparation to scalable, timely, and partially or fully automated agrometeorological advisory services in the future.

Crop Weather Calendars (CWCs) have traditionally served as important decision-support tools by linking crop phenological stages with prevailing and forecasted weather conditions to guide farm operations such as sowing, irrigation, nutrient management, and plant protection under the GKMS framework. However, conventional CWCs in India are largely static, assuming fixed sowing dates and uniform crop durations, and therefore fail to capture interannual variability in monsoon onset, varietal differences, and in-season weather stresses. These limitations constrain their usefulness for automated advisory generation, which requires dynamic, data-driven inputs. To overcome these gaps, the IMD, in collaboration with ICAR–CRIDA, Hyderabad, developed the Dynamic Crop Weather Calendar (DCWC) framework. Unlike static calendars, DCWC integrates long-term crop–weather relationships with real-time weather observations, medium-range forecasts, satellite-derived indicators, and field-level feedback, enabling continuous updating of crop phenophase progression during the growing season. From an automation perspective, DCWC provides an objective, rule-based structure for linking observed and forecasted weather conditions with crop growth stages (Fig.2). This enables automated translation of weather information into crop and stage-specific agrometeorological advisories with minimal manual intervention. When coupled with IMD's observational network and satellite-based crop monitoring, DCWC acts as a core input for agromet decision support systems, supporting the transition from expert-driven advisories to scalable, consistent, and timely semi-automated and fully automated agrometeorological advisory services under GKMS.

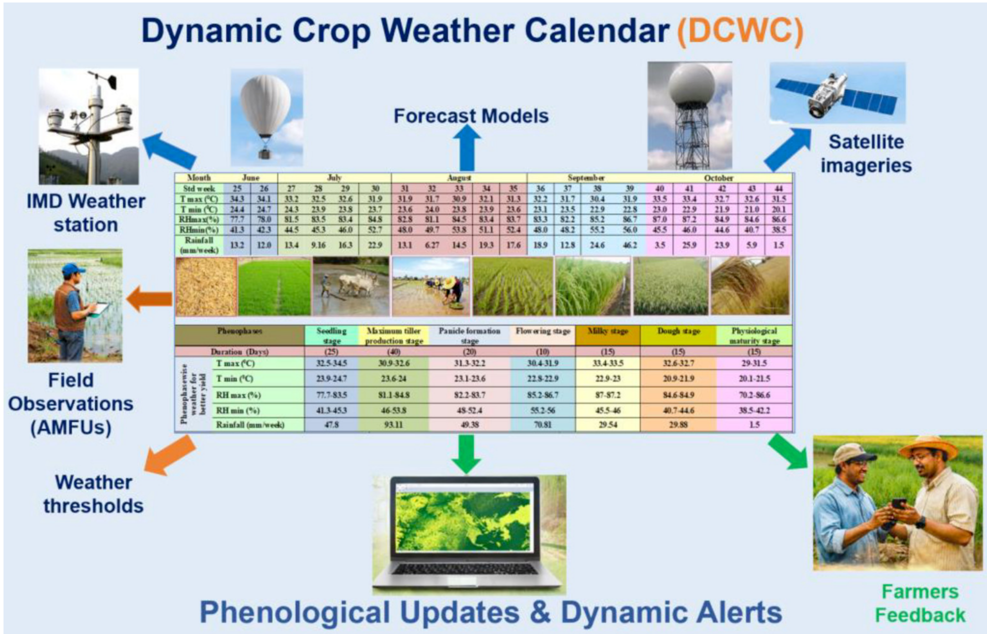

Fig. 2. Operational DCWC framework integrating weather observations, satellite-derived vegetation indices, and field feedback for phenophase-based agromet advisories.

Next-generation Decision Support System (DSS) is critical for enabling the automation and effective visualization of agrometeorological advisories by integrating diverse datasets and translating complex information into clear, actionable guidance for farmers and stakeholders. Such DSS platforms facilitate seamless ingestion of real-time weather observations, numerical forecasts, satellite-derived vegetation indices, soil moisture information, and dynamic crop weather calendars, and apply rule-based logic, crop models, and AI/ML techniques to generate crop and phenophase-specific advisories with minimal manual intervention. Advanced visualization capabilities further enhance interpretation by presenting weather risks, crop status, and advisory outputs in intuitive, map-based and dashboard formats, supporting timely decision-making and rapid dissemination. Recognizing this need, the IMD is developing an in-house next-generation DSS to support the progressive automation of agrometeorological advisories under the GKMS framework. The system is being designed to integrate multi-source observational and forecast data, satellite-based crop indicators, and field-level feedback, enabling consistent, scalable, and timely delivery of location-specific agromet advisories and strengthening climate-resilient agricultural services across the country.

Weather variability and extreme events increasingly affect not only field crops but also allied agricultural sectors such as livestock, horticulture, inland fisheries, poultry, and dairy, where weather-induced stresses directly influence productivity, health, and economic returns. High temperature and humidity lead to heat stress in livestock and poultry, increasing disease incidence and reducing milk, meat, and egg productivity. In horticulture, weather extremes such as heat waves, frost, unseasonal rainfall, and high humidity significantly influence flowering, fruit set, quality, and pest and disease outbreaks. Inland fisheries are highly sensitive to weather-driven changes in pond water temperature, rainfall, wind, and evaporation, which affect water quality, dissolved oxygen, algal blooms, and fish health. Despite this high vulnerability, sector-specific, impact-based weather advisories for allied agricultural sectors remain limited, and farmers often depend on generalized forecasts that inadequately support operational decision-making. To address these gaps, the IMD, under the GKMS Scheme, has initiated and strengthened collaborations with select ICAR institutes to develop sector-specific weather-based advisories. These include collaboration with the Directorate of Poultry Research (ICAR-DPR), Hyderabad for poultry; the Indian Institute of Horticultural Research (ICAR-IIHR), Bengaluru for horticulture; the Central Institute of Freshwater Aquaculture (ICAR-CIFA), Bhubaneswar for inland fisheries; and for livestock and dairy, partnerships with the National Institute of Veterinary Epidemiology and Disease Informatics (ICAR-NIVEDI), Bengaluru, and the National Dairy Research Institute (NDRI), Karnal (Fig.3). By integrating IMD's real-time observations and weather forecasts with sector-specific expertise from ICAR centres, these collaborations aim to develop scientifically robust, impact-based advisories and support their integration into next-generation decision support systems for timely, scalable, and eventually automated agrometeorological advisory services for crops and allied sectors.

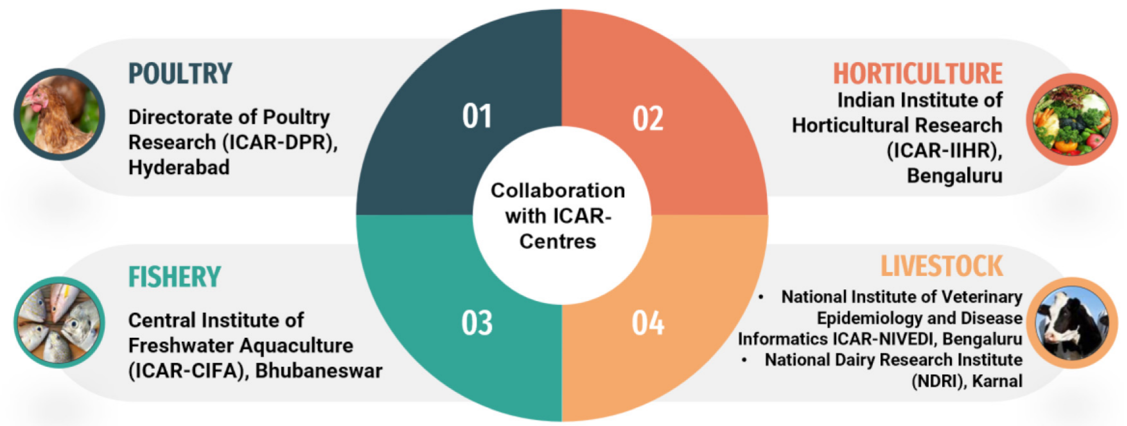

Fig. 3. Initiative under IMD's GKMS Scheme for Sector-Specific Weather-Based Advisories through Collaboration with ICAR Centres

At present, the IMD disseminates weather forecasts and agrometeorological advisories under the GKMS framework through multiple channels, including mobile applications such as Meghdoot and MAUSAM (Fig.4), SMS alerts via the mKisan platform, state government IT portals, web-based dashboards, social media, print and electronic media, and extension networks involving AMFUs, DAMUs, Krishi Vigyan Kendras, and Panchayati Raj institutions. This multi-channel approach enables IMD to reach millions of farmers across diverse agro-climatic regions with regular and event-based advisories. However, the preparation and dissemination process is still partly manual, which can limit the speed, frequency, and spatial granularity of advisories, especially during rapidly evolving weather events. Automation of agromet advisories through next-generation DSS will significantly strengthen this outreach by enabling faster generation of location- and crop-specific advisories and their near real-time dissemination across existing digital channels. Automated systems can trigger advisories immediately after forecast updates or threshold exceedances, ensuring that farmers receive critical information within narrow decision windows. Enhanced personalization at block or village level, combined with seamless integration with mobile apps, SMS, and web platforms, will further improve accessibility and usability. By delivering timely, targeted, and impact-based advisories at scale, automation will help farmers take preventive actions more effectively, thereby reducing weather-related crop losses, input wastage, and livelihood risks.

Fig. 4. IMD mobile platforms (MAUSAM and Meghdoot) enabling digital outreach of weather forecasts and agromet advisories under GKMS

Under the GKMS framework, the IMD has also institutionalized dynamic, in-season and end-of-season farmer feedback mechanisms to assess the relevance, usability, and impact of agrometeorological advisories on farm decision-making. At present, feedback is collected through AMFUs and DAMUs networks, field surveys, and interactions with farmers, capturing information on advisory adoption, perceived usefulness, yield benefits, and loss reduction during specific weather events. While these feedback processes provide valuable qualitative and quantitative insights, they are largely manual and episodic, limiting their timeliness, spatial coverage, and analytical depth. Automation of agrometeorological advisories under GKMS will significantly enhance farmer feedback systems by enabling digital, real-time, and geo-referenced feedback collection through mobile applications, web platforms, and SMS-based interfaces, closely linked with advisory dissemination channels. Automated systems can facilitate structured feedback aligned with crop stage, advisory type, and weather events, allowing continuous monitoring of advisory effectiveness across regions and sectors. Integration of such feedback into decision support systems and analytics platforms, supported by AI/ML tools, will enable rapid aggregation, pattern recognition, and impact assessment, providing objective evidence for refining advisory rules, thresholds, and delivery strategies. This closed-loop framework linking forecasts, advisories, farmer responses, and outcomes will strengthen the responsiveness, credibility, and adaptive learning capacity of the GKMS programme and support the evolution of more precise, farmer-centric, and impact-driven agrometeorological advisory services.

Automation of agrometeorological advisories for crops and allied agricultural sectors can be substantially enhanced through the infrastructure strengthening, data integration, and digital transformation envisaged under Mission Mausam of the Ministry of Earth Sciences (MoES).

Expansion and modernization of observational networks such as AWS, Agro-AWS with soil and microclimate sensors, Doppler Weather Radars, satellite-based observations, and high-performance computing systems, complemented by the Weather Information Network and Data System (WINDS) a collaborative initiative of the Ministry of Agriculture & Farmers Welfare (MoA&FW) and the IMD provide high-resolution, quality-controlled, and real-time weather datasets essential for automated advisory generation. These multi-source observations and forecasts, when assimilated into integrated data platforms, can be systematically linked with crop- and sector-specific vulnerability thresholds, agro-climatic calendars, and management practices to enable impact-based advisory services. Embedding expert-validated, rule-based logic and AI/ML-assisted models, developed jointly by IMD and concerned ICAR institutes, within DSS enables automated translation of weather signals into sector- and activity-specific advisories, such as heat stress and disease risk alerts for livestock and poultry, weather-sensitive management advisories for horticulture, and rainfall- and temperature-driven water quality advisories for inland fisheries, with progressively reduced manual intervention. Strengthened institutional collaboration and linkage with MoA&FW extension systems and Panchayati Raj Institutions support timely, location-specific, and scalable dissemination, facilitating a phased transition from semi-automated to near-real-time, end-to-end automated agrometeorological advisory services under GKMS and enhancing climate resilience across agriculture and allied sectors.

The Role of Natural Farming in Green Agriculture: Pathway Toward Sustainable Food Systems

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Introduction

21st-century agricultural systems worldwide are undergoing a paradigm shift in response to growing concerns about the sustainability of conventional, high-input agriculture. After decades of chemical-intensive farming that boosted yields during the Green Revolution, agriculture now confronts a dual crisis: environmental degradation and declining ecological resilience. Globally, 33% of soils are moderately to highly degraded (FAO, 2022), and agriculture accounts for nearly 25% of anthropogenic greenhouse gas emissions (IPCC, 2021). Progressive soil degradation, declining soil organic carbon, depletion of groundwater resources, increased greenhouse gas emissions, loss of biodiversity, and stagnation or decline in total factor productivity have emerged as major challenges to sustainable agricultural development. These concerns are further exacerbated by projections indicating that global food demand is expected to increase by nearly 50% by 2050 (FAO, 2020), necessitating a transition toward resource-conserving, climate-resilient, and environmentally sustainable agricultural systems. In this context, the concept of Green Agriculture has gained prominence as an integrative approach aimed at achieving sustainable intensification through efficient use of natural resources, reduction in environmental footprints, and enhancement of system resilience. Within this framework, Natural Farming (NF) has emerged as a promising production system that aligns closely with the principles (Fig. 1) of sustainable agriculture and agroecology (Singh *et al.*, 2021). Natural Farming is based on the premise that agricultural productivity can be sustained by harnessing and strengthening natural ecological processes rather than relying on external synthetic inputs. Key components of NF include minimizing the use of chemical fertilizers and pesticides, enhancing soil biological activity, recycling on-farm organic resources, promoting beneficial microorganisms, and restoring soil health and ecosystem services. In the Indian context, Natural Farming approaches such as Zero Budget Natural Farming (ZBNF) and the Bharatiya Prakritik Krishi Paddhati (BPKP) have been promoted by national and state governments as low-input, cost-effective alternatives to conventional farming, particularly for small and marginal farmers. These approaches are consistent with ICAR's emphasis on soil health management, input-use efficiency, climate-smart agriculture, and sustainable livelihood security. At the global level, the principles of Natural Farming are conceptually aligned with agroecology, regenerative agriculture, and ecological farming systems, including the philosophies advocated by Masanobu Fukuoka. This chapter examines the role of Natural Farming within the broader paradigm of Green Agriculture, with specific emphasis on its guiding principles, scientific rationale, impacts on crop productivity and soil health, environmental implications, constraints to adoption, evidence from field-based case studies, and prospects for large-scale dissemination through research, extension, and policy support.

Fig. 1. Principles of Natural Farming

Conceptual Framework of Natural Farming

Historical Context and Conceptual Basis of Natural Farming

Natural farming can be understood as a biologically regulated approach to agroecosystem management, whose conceptual foundations are rooted in long-standing indigenous cultivation systems. These systems operated primarily through internally mediated ecological processes rather than externally supplied chemical inputs. Their functional persistence was governed by active soil food webs, continuous organic matter turnover, and tight coupling between carbon and nutrient cycles, which collectively sustained nutrient availability, soil structure, and biological regulation under minimal anthropogenic disturbance. The modern theoretical articulation of natural farming was influenced by Masanobu Fukuoka's "do-nothing" philosophy (Fukuoka, 1978), which, from a soil ecological standpoint, represents a rejection of disturbance-driven agroecosystem control. Intensive tillage, mineral fertilization, and pesticide application were viewed as exogenous perturbations that disrupt soil microbial networks, decouple carbon–nitrogen–phosphorus (C–N–P) cycling, and reduce the functional redundancy of soil biota. Fukuoka's emphasis on minimal soil disturbance and surface residue retention implicitly aligns with contemporary understanding of soil aggregation dynamics, microbial habitat preservation, and rhizosphere-mediated nutrient transformations.

In the Indian context, these ecological principles were operationalized through Zero Budget Natural Farming (ZBNF), which seeks to reorient nutrient and energy flows within the farm system toward biological pathways, emphasizing locally derived inputs like Jeevamrita (microbial culture), Bijamrita (seed inoculant), Acchadana (mulching), and Whapasa (soil moisture management). Collectively, these practices embody a closed-loop bioeconomic model, consistent with agroecological and circular economy principles. Inputs such as Jeevamrita and Bijamrita function not as direct nutrient sources but as microbial inoculants and metabolic stimulants, enhancing enzymatic activity, microbial biomass turnover, and the mineralization–immobilization balance in soils. Their repeated application is intended to intensify microbial-mediated nutrient release from native soil organic matter and crop residues, thereby strengthening internal nutrient cycling and reducing dependence on externally derived fertilizers. Practices such as Acchadana (mulching) and Whapasa (soil moisture regulation) address the physical and biogeochemical controls on soil biological activity. Mulching moderates soil temperature, reduces evaporative losses, and provides labile and recalcitrant carbon substrates that sustain heterotrophic microbial communities and promote aggregate stability. Whapasa, conceptualized as an optimal balance between soil air and water, directly influences oxygen diffusion, redox potential, and microbial respiration, thereby regulating nutrient transformation processes such as nitrification, denitrification, and phosphorus solubilization in the rhizosphere.

Table 1. Environmental Performance Indicators

Environmental Metric	Conventional System	Natural Farming System	Net Benefit
Nitrous oxide emissions	High (N fertilizer-based)	40–60% lower	Reduced GHG footprint
Soil organic carbon	Depleting trend	Increasing (0.3–0.5 Mg ha^{-1} yr^{-1})	Improved soil fertility
Biodiversity index	Monoculture dominance	High species richness	Pollinator and predator stability
Water-use efficiency	Moderate	25–40% improved	Reduced irrigation dependency
Residue management	Burning common	Composting and mulching	Prevents air pollution

(Sources: Mishra *et al*., 2020; Patra *et al*., 2023)

From a biogeochemical systems perspective, natural farming represents a shift from input-driven nutrient supply to process-driven nutrient regulation. Crop productivity under such systems is sustained through enhanced biological nutrient cycling, improved synchronization between nutrient release and plant demand, and stabilization of soil organic carbon pools. The conceptual convergence of natural farming with agroecology, regenerative agriculture, and circular bioeconomy frameworks reflects a shared theoretical emphasis on soil as a living, self-organizing system, where long-term productivity is governed by ecological feedbacks, biotic interactions, and efficient internal resource turnover, rather than by short-term chemical supplementation.

Theoretical Foundation of Green Agriculture

Green agriculture is grounded in an integrative theoretical framework that recognizes agricultural systems as coupled human–natural systems governed by ecological, economic, and social feedbacks. At its core, green agriculture seeks to reconcile productivity goals with the preservation of ecosystem integrity by prioritizing the regulation of biophysical processes over the maximization of external inputs. Conceptually, it rests on three interdependent pillars—ecological integrity, economic viability, and social equity—which together define the functional boundaries within which agricultural intensification must occur (UNEP, 2020). From an ecological standpoint, green agriculture emphasizes the optimization of ecosystem functions such as soil nutrient cycling, biological nitrogen fixation, carbon sequestration, pollination services, and natural pest regulation. Rather than relying on linear, input-driven nutrient supply, the framework promotes process-based management that enhances internal nutrient turnover, stabilizes soil organic matter pools, and strengthens trophic interactions across soil and aboveground food webs. This shift reflects contemporary ecological theory, which recognizes that ecosystem efficiency and resilience increase with functional diversity, redundancy, and tight coupling of biogeochemical cycles.

Natural farming represents a practical instantiation of these theoretical principles by reorienting agricultural management toward biologically mediated regulation of soil and crop processes. By minimizing synthetic inputs and emphasizing microbial activation, organic residue retention, and soil cover, natural farming enhances the efficiency of carbon–nutrient coupling and promotes closed-loop nutrient cycling within the agroecosystem. Increased microbial biomass and enzymatic activity facilitate nutrient mineralization–immobilization dynamics that are more closely synchronized with crop demand, thereby improving nutrient-use efficiency while reducing losses through leaching, volatilization, and runoff. In parallel, the promotion of plant and soil biodiversity under natural farming strengthens ecosystem multifunctionality. Diverse microbial and faunal communities contribute to improved soil structure, enhanced water infiltration and retention, and greater buffering capacity against climatic variability. Reduced reliance on energy-intensive agrochemicals lowers the greenhouse gas footprint of production systems, both directly through decreased emissions and indirectly through the stabilization of soil organic carbon stocks. Beyond biophysical processes, green agriculture explicitly incorporates socio-economic dimensions, recognizing that ecological sustainability is contingent upon economic feasibility and social resilience. Natural farming contributes to these dimensions by lowering input costs, reducing exposure to market volatility, and enhancing adaptive capacity at the farm household level. In this sense, natural farming operationalizes the theoretical construct of green agriculture by translating ecosystem-based principles into field-level management practices that simultaneously address productivity, environmental sustainability, and livelihood security.

Scientific and Ecological Mechanisms Underpinning Natural Farming

Soil Microbial Ecology and Carbon Sequestration

Soil microorganisms constitute the primary biological drivers of productivity and stability in natural farming systems. The recurrent application of organic substrates such as farmyard manure, cow dung-based formulations, crop residues, and compost provides both energy and nutrient sources that stimulate microbial biomass and functional diversity. Enhanced populations of diazotrophic bacteria (e.g., *Rhizobium*, *Azospirillum*), phosphate-solubilizing microorganisms, and arbuscular mycorrhizal fungi play a central role in regulating nutrient availability and carbon turnover within the soil matrix (Gupta *et al*., 2022). From a biogeochemical perspective, these microbial consortia contribute to carbon sequestration through multiple pathways, including microbial assimilation of organic carbon, formation of stable microbial residues, and promotion of organo–mineral associations that protect soil organic matter from rapid decomposition. Fungal-derived compounds such as glomalin and microbial extracellular polysaccharides enhance aggregate formation, thereby improving soil structural stability, porosity, and water retention while physically stabilizing organic carbon within microaggregates. Empirical evidence indicates that sustained organic management under natural farming can increase soil organic carbon stocks by approximately 0.3–0.5 Mg ha^{-1} yr^{-1}, corresponding to a mitigation potential of up to 1.8 t CO_2 ha^{-1} yr^{-1} (Patra *et al*., 2023), underscoring its relevance for climate change mitigation.

Biogeochemical Regulation of Nutrient Cycling

Natural farming operates through the optimization of the soil–plant–microbe continuum, wherein nutrient availability is governed by biologically mediated mineralization–immobilization dynamics rather than direct chemical supplementation. Elevated activities of key soil enzymes, including dehydrogenase, urease, phosphatase, and â-glucosidase, reflect intensified microbial metabolism and enhanced turnover of organic substrates. These enzymatic processes regulate the gradual release of nitrogen, phosphorus, and other nutrients from organic pools, ensuring sustained nutrient availability over the crop growth cycle. In contrast to synthetic fertilizer-based systems, which often induce transient nutrient surpluses and associated losses through leaching, volatilization, or fixation, natural farming systems promote nutrient synchronization, aligning nutrient release with plant uptake demand. This process-based regulation enhances nutrient-use efficiency, reduces environmental losses, and stabilizes soil fertility over time, particularly in low-input and rainfed agroecosystems.

Ecological Regulation of Pests and Diseases

Pest and disease management in natural farming is embedded within the broader framework of ecological regulation rather than direct chemical suppression. Botanical extracts such as neem (*Azadirachta indica*), cow urine-based formulations, and microbial antagonists, including *Trichoderma* spp. and *Bacillus subtilis,* function as biopesticides by inhibiting pathogen growth, inducing systemic resistance, and disrupting pest life cycles. These biologically based inputs exert selective pressure without destabilizing non-target organisms or beneficial soil biota. At the landscape and field scale, practices such as intercropping, crop diversification, and integration of agroforestry components enhance habitat complexity and provide refugia for natural enemies, including parasitoids and predatory insects. This trophic regulation reduces the probability of pest outbreaks while simultaneously supporting pollinator populations and overall agroecosystem resilience (Kumar *et al*., 2021).

Soil–Water Dynamics and Conservation Mechanisms

Water-use efficiency in natural farming systems is primarily mediated through improvements in soil physical and biological properties. Surface mulching, cover cropping, and increased soil organic matter content enhance water-holding capacity, infiltration rates, and capillary conductivity, thereby reducing evaporative losses and improving plant-available water. Improved aggregation and pore continuity facilitate deeper root penetration and more efficient soil moisture extraction under water-limited conditions. The Whapasa principle, which emphasizes maintaining an optimal balance of soil air and moisture in the root zone, directly influences microbial respiration, root physiology, and nutrient diffusion. Empirical studies indicate that adoption of Whapasa-based moisture management can reduce irrigation requirements by 25–40% (Ramesh *et al.*, 2021), making it particularly relevant for climate adaptation in semi-arid and drought-prone regions.

Socio-Economic and Livelihood Dimensions of Natural Farming

Economic Viability and System Resilience

From a systems perspective, the economic viability of natural farming emerges from a structural shift in the production function—from dependence on externally purchased inputs to reliance on internally regulated biological processes. By minimizing synthetic fertilizers, pesticides, and energy-intensive inputs, natural farming substantially reduces variable costs of cultivation without proportionate declines in productivity. Empirical evidence from large-scale field implementations, such as those in Andhra Pradesh, indicates reductions in input costs of approximately 60–70%, with net returns per unit area remaining comparable or marginally higher due to cost savings and improved input-use efficiency (Mishra *et al.*, 2020). Beyond short-term profitability, natural farming enhances economic resilience by stabilizing the biophysical foundations of production. Improvements in soil organic carbon stocks, nutrient buffering capacity, and water retention reduce yield variability under climatic stress, thereby lowering production risk. In economic terms, this translates into reduced exposure to input price volatility and diminished dependence on credit-driven input markets. Such risk-buffering capacity is increasingly recognized as a critical criterion for inclusive green growth, particularly in smallholder-dominated agrarian economies where market shocks and climatic variability disproportionately affect farm livelihoods.

Gender, Social Capital, and Collective Agency

The socio-ecological functioning of natural farming systems is closely intertwined with gendered knowledge systems and community-level governance structures. Women farmers often serve as primary custodians of indigenous ecological knowledge, including seed selection, varietal conservation, composting practices, and botanical pest management. Their active participation and leadership in natural farming collectives facilitate the preservation and intergenerational transmission of locally adapted knowledge, which is essential for maintaining system diversity and resilience (Khadse *et al.*, 2018). At the community scale, collective engagement in input preparation, seed exchange, and on-farm experimentation strengthens social capital and reinforces norms of reciprocity and shared resource management. These social mechanisms enhance equity in benefit distribution and improve collective decision-making capacity, contributing to more inclusive and adaptive agrarian institutions. From a political ecology perspective, such collective agency counterbalances the asymmetries created by input- and market-driven agricultural models, repositioning farmers—particularly women—as active agents in agroecological transitions.

Knowledge Ecology, Learning Processes, and Innovation Dynamics

Unlike conventional agricultural systems, which are largely driven by standardized external inputs and top-down technological dissemination, natural farming operates as a knowledge-intensive and context-specific production system. Its performance depends critically on farmers' understanding of soil biological processes, crop–environment interactions, and adaptive management strategies. Consequently, decentralized knowledge ecologies, characterized by farmer-to-farmer learning, participatory research, and experiential field-based experimentation, serve as the primary engines of innovation and scaling. These social learning processes enable continuous feedback between ecological responses and management decisions, allowing farmers to iteratively refine practices in response to local soil, climate, and crop conditions. Such adaptive co-production of knowledge enhances system flexibility and reduces technological lock-in, which is often associated with input-intensive agriculture. From an innovation systems perspective, the strength of natural farming lies not in technological standardization but in its capacity to foster locally embedded, ecologically informed innovation pathways that are resilient under environmental and socio-economic uncertainty.

Studies and Empirical Evidence

Community-Managed Natural Farming in India

The Community-Managed Natural Farming (CMNF) program implemented by the Government of Andhra Pradesh represents one of the most extensive real-world experiments in biologically regulated agriculture, encompassing over 600,000 farmers across diverse agroecological zones. From a soil ecological perspective, the program demonstrates how large-scale substitution of synthetic inputs with biologically active formulations and organic residue management can enhance soil microbial functional diversity and strengthen nutrient cycling processes. Independent evaluations report measurable improvements in soil microbial diversity indices, indicative of enhanced soil food-web complexity and functional redundancy (FAO, 2022). Economically, the CMNF model illustrates a transition from input-intensive to cost-efficient production systems. Reductions in expenditure on fertilizers and pesticides translate into 15–25% higher net farm incomes, even in the absence of substantial yield gains. This decoupling of profitability from yield maximization reflects a restructuring of the agricultural production function toward efficiency and risk reduction rather than output intensification. From a political ecology perspective, the community-managed institutional architecture, centered on farmer collectives, women-led self-help groups, and decentralized extension, repositions knowledge and resource governance at the local level, reducing dependence on external markets while strengthening social capital and collective agency.

Fukuoka's Ecological Model and Long-Term System Stability in Japan

Masanobu Fukuoka's long-term experiments in Japan provide foundational empirical evidence for the ecological viability of minimal-disturbance farming systems. His non-tillage, residue-retentive, and biologically enriched rice–barley rotations sustained yields at approximately 90–95% of conventional systems over multiple decades (Fukuoka, 1978). From a biogeochemical standpoint, these outcomes highlight the capacity of undisturbed soil systems to maintain stable carbon and nutrient cycling through continuous organic matter inputs, active microbial mediation, and preserved soil structural integrity. The significance of Fukuoka's work lies less in short-term productivity metrics and more in its demonstration of long-term agroecosystem resilience. By avoiding chronic soil disturbance and chemical perturbation, the system maintained functional equilibrium across climatic variability and pest pressures. In contemporary terms, this model anticipates resilience theory and disturbance ecology, illustrating how reduced anthropogenic interference can preserve system self-regulation and buffer agroecosystems against cumulative degradation.

Agroecological Transitions and Food Sovereignty in Latin America

Experiences from Brazil, Cuba, and Mexico illustrate how natural farming principles have been embedded within broader agroecological and food sovereignty frameworks at national and regional scales. These transitions emphasize diversified cropping systems, green manuring, biological pest control, and recycling of organic residues to restore soil fertility and reduce dependence on imported agrochemicals (Altieri & Nicholls, 2020). Empirical assessments report enhanced nutrient recycling efficiency, improved soil organic matter dynamics, and increased livelihood stability among smallholder and peasant farming communities. From a political ecology and knowledge systems perspective, Latin American agroecological transitions are characterized by strong horizontal knowledge exchange, farmer-led experimentation, and institutional support for participatory research. These processes challenge technocratic, input-centric development models by prioritizing locally adapted innovation and collective governance. Economically, the emphasis on diversified production and local markets reduces vulnerability to global price shocks, while ecologically, enhanced biodiversity and soil function contribute to climate resilience and long-term sustainability.

Climate Change Mitigation and Adaptation Potential of Natural Farming

Natural farming contributes to climate resilience through the coupled pathways of greenhouse gas mitigation and agroecosystem adaptation, both of which are mediated primarily by soil biological and biogeochemical processes. From a mitigation perspective, the replacement of synthetic fertilizers with biologically regulated nutrient sources reduces emissions associated with fertilizer manufacture, transport, and application, particularly nitrous oxide derived from reactive nitrogen inputs. Concurrently, sustained organic matter inputs and reduced soil disturbance enhance soil organic carbon stabilization through microbial processing, aggregate formation, and organo–mineral associations, thereby increasing terrestrial carbon sinks. Life-cycle assessments integrating on-farm emissions, input substitution, and soil carbon dynamics indicate that natural farming systems can reduce net greenhouse gas emissions by approximately 1.2–1.8 t CO_2-eq ha^{-1} yr^{-1} relative to conventional, input-intensive agriculture (Patra *et al.*, 2023). These reductions arise from a combination of lower fossil energy use, decreased nitrogen-induced emissions, and incremental carbon sequestration, highlighting the importance of process-based management in lowering the emission intensity of food production systems. Beyond mitigation, natural farming enhances climate adaptation by strengthening the biophysical buffering capacity of agroecosystems. Increased soil organic carbon and improved aggregation enhance water-holding capacity, infiltration, and soil structural resilience, reducing sensitivity to drought stress and extreme rainfall events. Enhanced biological diversity—both aboveground and within the soil food web—improves functional redundancy and ecological regulation, thereby stabilizing crop performance under fluctuating climatic conditions and reducing vulnerability to pest and disease outbreaks. From a systems perspective, the adaptive advantage of natural farming lies in its emphasis on soil-mediated regulation rather than external control. By improving soil moisture dynamics, nutrient buffering, and biological self-regulation, natural farming reduces dependence on climate-sensitive inputs and reactive interventions. Collectively, these attributes position natural farming as a climate-resilient agricultural strategy that integrates mitigation and adaptation within a unified soil-centered framework, aligning long-term productivity with environmental sustainability under increasing climatic uncertainty.

Policy, Institutional, and Research Dimensions

Government Initiatives and Policy Architecture

The institutionalization of natural farming within national and international policy frameworks reflects a broader shift toward sustainability-oriented agricultural governance. In India, the Bharatiya Prakritik Krishi Paddhati (BPKP), implemented under the Paramparagat Krishi Vikas Yojana (PKVY), represents a formal policy attempt to mainstream natural farming through financial assistance, capacity building, and institutional recognition. By emphasizing reduction of synthetic inputs and restoration of soil health, BPKP aligns with national priorities related to soil organic carbon enhancement, climate resilience, and smallholder livelihood security. Globally, analogous policy signals are evident in the European Union's Farm to Fork Strategy and Africa's Agenda 2063, which prioritize reductions in chemical pesticide and fertilizer use, promotion of soil carbon sequestration, and transition toward agroecological production systems. From a political economy perspective, these initiatives reflect an emerging consensus that long-term food security and climate goals cannot be achieved through input-intensive models alone, but require reconfiguration of incentives toward ecosystem-based agricultural management.

Research Systems and Academic Integration

The scientific validation and refinement of natural farming depend critically on its integration into formal research and academic institutions. Organizations such as ICAR, FAO, and CIMMYT have initiated long-term, field-based experiments to assess yield stability, soil carbon dynamics, nutrient fluxes, microbial ecology, and system resilience under natural farming regimes. Such trials are essential for disentangling short-term transitional effects from long-term equilibrium responses in soil–plant–microbe systems. From a knowledge systems perspective, incorporation of natural farming into university curricula and research programs represents a shift from technology-centric to process-centric agricultural science. This transition facilitates interdisciplinary inquiry spanning soil biogeochemistry, systems ecology, agronomy, and socio-economic analysis, while also legitimizing farmer-generated knowledge within formal scientific discourse. The co-production of knowledge between researchers and practitioners is thus central to advancing both scientific rigor and contextual relevance.

Certification, Markets, and Institutional Trust

Scaling natural farming beyond subsistence or localized adoption requires institutional mechanisms that translate ecological value into economic signals. Credible certification and eco-labelling systems are critical for differentiating natural farming produce in markets and rewarding ecosystem service provision. Participatory Guarantee Systems (PGS) offer context-appropriate, low-cost alternatives to third-party certification, particularly for smallholder-dominated systems, by embedding trust within community-based verification processes. Emerging digital tools, including blockchain-based traceability platforms, have the potential to further enhance transparency, reduce information asymmetry, and connect producers with sustainability-conscious consumers. From an institutional economics standpoint, such mechanisms help internalize environmental externalities and align market incentives with ecological performance, thereby supporting the commercial viability of natural farming systems.

Limitations and Scientific Challenges

Despite its ecological and socio-economic promise, natural farming faces several unresolved scientific and operational challenges that constrain its widespread adoption. Transitional yield variability remains a critical concern, as agroecosystems undergoing shifts from chemically regulated to biologically regulated nutrient cycles may experience temporary yield reductions before soil microbial communities and nutrient equilibria stabilize. These dynamics underscore the importance of temporal scale in evaluating system performance. Significant data gaps persist, particularly with respect to long-term, multi-location quantification of soil carbon sequestration rates, greenhouse gas fluxes, and nutrient budgets across diverse agroecological contexts. Methodological heterogeneity and limited replication further complicate synthesis and meta-analysis. Additionally, existing agricultural subsidy regimes often exhibit policy asymmetry, disproportionately favoring chemical-intensive inputs and thereby distorting comparative economic assessments of natural farming. Standardization presents another challenge, as the composition and efficacy of microbial inoculants and organic formulations vary widely across regions and preparation methods. Addressing these limitations requires rigorous, interdisciplinary research that integrates soil biogeochemistry, systems ecology, agronomic experimentation, and socio-economic modeling within harmonized analytical frameworks.

Conclusion

Natural farming transcends the notion of a nostalgic return to traditional practices; it constitutes a science-informed, climate-responsive, and socio-economically relevant agricultural paradigm grounded in contemporary understanding of soil ecology, biogeochemical cycling, and agroecosystem resilience. By prioritizing biological regulation over chemical control, natural farming realigns agricultural production with the functional integrity of soil–plant–microbe systems, thereby enhancing long-term productivity while reducing ecological externalities. Through the reactivation of soil microbial networks, enhancement of below- and above-ground biodiversity, and partial closure of nutrient and carbon loops, natural farming facilitates a shift from extractive input-dependent agriculture to regenerative, process-driven systems. These mechanisms underpin its capacity to contribute meaningfully to climate change mitigation and adaptation (SDG 13) by increasing soil carbon stocks, lowering synthetic nitrogen dependence, and improving system resilience to climatic extremes. Equally important are its socio-economic implications. Reduced reliance on purchased inputs lowers production costs and risk exposure for smallholders, directly supporting poverty alleviation and livelihood security (SDG 1). The knowledge-intensive and locally adaptable nature of natural farming enhances opportunities for inclusive participation, particularly for women, by valorizing on-farm knowledge, labor, and decision-making—thereby contributing to gender equity in agrarian systems (SDG 5). At the macro level, the transition toward ecosystem-service-oriented agriculture fosters decent work, rural employment, and sustainable economic growth (SDG 8) by internalizing environmental values into production and market structures. The future trajectory of natural farming depends on its integration into formal scientific, institutional, and policy frameworks.

Advancing this transition will require systems-based research, harmonized methodologies, and policy realignment toward ecosystem service incentives. When supported by robust science and enabling institutions, natural farming holds the potential to evolve from a decentralized grassroots movement into a globally relevant, climate-aligned strategy for sustainable and equitable food systems.

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Non-Conventional Nutrient Sources in Transforming Green Agriculture in India

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Introduction

Deterioration of soil quality under modern intensive agricultural practices is very common due to indiscriminate use of agro-chemicals and synthetic fertilizers. Adoption of agricultural practices which can support present and future food and feed demand without hampering ecosystem services is of prime importance. Maintenance of soil fertility and supply of plant nutrition in intensive agriculture is more complex. Organic and inorganic wastes generated from farming as well industrial activities, and low-grade natural mineral resources and microbes that have potential to supply plant nutrients, correct soil problems and maintain soil health. Here, the scope of alternative sources of nutrients or non-conventional nutrient sources (NCNS) are discussed with their nutrient supplying capacities. This is not only a way to recycle or utilize the non-conventional materials as such but also can be used as alternative input sources with some modification.

The importance of fertilizers in enhancing crop productivity and ensuring food security cannot be overstated. India's fertilizer consumption has been on a steady rise since the Green Revolution. According to the Fertiliser Association of India (FAI, 2025), production of fertilizers in terms of $N+P_2O_5$ was 22.09 million tonne (Mt) in 2024-25 compared to 21.99 Mt in 2023-24. On the other hand, consumption of $N+P_2O_5+K_2O$ in 2024-25 has been 32.93 Mt compared to 30.64 Mt in 2023-24. The gap between consumption and production is met by import of finished products. Consumption of total fertilizer products has been about 70.7 Mt in 2024-25 compared to 64.8 Mt in 2023-24. This increase is reflective of ongoing agricultural activities and the continued reliance on chemical fertilizers to maintain crop yields. However, the distribution of fertilizer consumption across different regions of India is not uniform. States such as Punjab, Haryana, and Uttar Pradesh, which are major agricultural producers, exhibit significantly higher fertilizer usage per hectare compared to states in the northeastern region, where the adoption of chemical fertilizers is comparatively lower. This disparity is attributed to differences in agricultural practices, crop patterns, soil fertility, and availability of irrigation facilities. On the other hand, the heavy reliance on subsidies for fertilizers, particularly urea, poses a substantial financial burden on the government. These subsidies, while beneficial in making fertilizers affordable for farmers, have led to issues such as over-application and imbalanced use of fertilizers, particularly the overuse of urea. This imbalance can lead to soil degradation, reduced nutrient use efficiency, and a decline in agricultural productivity over the long-term. The government's efforts to promote balanced fertilizer use and reduce the subsidy burden include initiatives such as the introduction of neem-coated urea and the Soil Health Card scheme, which aims to provide farmers with soil health assessments and fertilizer recommendations. In response to these challenges, there is a growing emphasis on promoting sustainable agronomic practices and innovations in fertilizer use. Integrated nutrient management (INM) is one such approach that combines the use of chemical fertilizers with organic amendments such as compost, green manure, and biofertilizers to maintain soil fertility and enhance nutrient use efficiency. Various alternative approaches have been studied to make effective fertilizers application such as organic waste management, priming techniques, next generation fertilizers formulation and use of biofertilizers that not only reduce the nutrients losses but also improve the soil and environment health.

Non-conventional nutrients nutrient sources

In the wake of the Green Revolution, which prioritized high-yielding varieties and chemical intensification, Indian agriculture is now navigating a "second transition" toward Green Agriculture. This movement focuses on ecological sustainability, soil health, and resource efficiency. Central to this transformation is the shift from synthetic fertilizers to non-conventional nutrient sources (NCNS). The NCNS refer to biological, organic, or recycled inputs that were traditionally overlooked in favour of conventional fertilizers like urea and DAP. These sources—ranging from microbial biofertilizers to recycled organic wastes—are redefining how India feeds its soil while safeguarding its environment. In the context of Green Agriculture, the potential non-conventional fertilizer sources of plant nutrients are green manure crops, crop residues, organic manures, FYM, sewage sludge, oilcakes, blood meal, compost, phospho-compost, vermicompost, biogas slurry, agricultural wastes, press mud, biodynamic preparations, biofertilizers, bio-stimulants *etc*.

Living microbial inoculants such as *Rhizobium*, *Azotobacter*, and phosphate solubilizing microorganisms (PSM) as well as agro-industrial wastes/by-products like press-mud from sugar mills or spent wash from distilleries, oil cakes, and fruit processing wastes have significant potential. Liquid biofertilizers which have a longer shelf-life and are easier for farmers to use through drip irrigation systems (fertigation) can be promoted. Microbial rejuvenation using biofertilizers act as "living engines" in the soil. For instance, *Rhizobium* can fix 50-200 kg N ha^{-1} in the soil naturally. Nutrient bioavailability, particularly P can be improved. Many Indian soils are rich in P, but it is "locked" in insoluble forms. Phosphate solubilizing bacteria (PSB) release organic acids that make this recalcitrant or build-up P into plant available form, thereby reducing the need for imported chemical phosphates. Similarly, liquid seaweed extracts from marine algae and biostimulants that act as growth boosters and enhance the plant's internal nutrient-use efficiency can be utilized. Technologies that convert waste-to-wealth such as municipal solid wastes and agricultural residues (like rice straw) into nutrient-rich compost are helping to solve the twin problems of waste management and soil nutrition and reducing the input costs for farmers.

One of the core pillars of India's "Natural Farming" initiative is reducing dependence on expensive, imported chemical inputs. By using farm-made preparations like *Jeevamrit* (fermented cow dung and urine) and *Beejamrit* (seed treatment), farmers can achieve "Green Agriculture" status while keeping production costs low because Indian government spends billions on fertilizer subsidies. By promoting Zero Budget Natural Farming (ZBNF) and the PM-PRANAM scheme, the state aims to reduce this fiscal drain while encouraging farmers to use fermented organic formulations like *Beejamrit* (seed treatment) and *Jeevamrit* (soil inoculant).

The most significant impact of non-conventional nutrients is the restoration of soil health. Decades of chemical farming have led to soil carbon depletion and the destruction of microbial life.

Traditional urea application has led to soil acidification and a decline in soil organic carbon (SOC). Non-conventional sources like vermicompost and green manures (e.g., *Dhaincha*) replenish organic matter. This biological "recharge" allows the soil to act as a carbon sink, mitigating climate change and thus restoring the "Living Soil". Use of non-conventional nutrient sources improve physical, chemical and biological properties of the soil. It improves soil structure, soil aeration, and water holding capacity. Minimizing soil erosion by up to 50% and increasing crop yields up to five-fold within 5 years. Non-conventional fertilizer provides all the nutrients that are required by plants but in limited quantities. It helps in maintaining C:N ratio in the soil and also increases the fertility and productivity of the soil. They supply nutrients in a balanced ratio and stimulate soil flora and fauna. Due to increase in the biological activity, the nutrients that are in the lower depths are made available to the plants.

Organic wastes utilization

Organic fertilizers, including animal manures, crop residues, green manures, and composts were traditionally and preferentially used in developing countries until the 1960s when chemical fertilizers began to gain in popularity. Chemical fertilizers became easily available and unlike organic fertilizers they were less bulky and, thus, easier to transport, handle, and store. They were also relatively inexpensive and produced more striking results than organic fertilizers, particularly during the era of the "Green Revolution" when crop varieties were introduced that responded best to heavy applications of chemical fertilizers. The shift away from organic recycling practices also served to re-emphasize the value of, and need for organic amendments for the short- and long-term improvement of cultivated soils and maintenance of soil productivity. Without regular additions of adequate amounts of organic materials to soils, there is increased leaching, erosion, and gradual deterioration of their physical properties. Moreover, as the soil degrades, there is a concomitant decrease in the crop use efficiency of chemical fertilizers, especially N. Environmental pollution has also become an international concern. Thus, proper processing and recycling of organic wastes as resources for agriculture can greatly reduce environmental pollution. Additional benefits include improved public health, conservation of resources, and better appearance of both urban and rural communities.

A recent assessment of organic recycling states that the improvement of soil productivity as a whole is expected to contribute about 60% of the increased food production that is currently needed worldwide. Much of this goal can be achieved through proper management of agro-industrial and municipal wastes as alternate source of nutrients as well as organic matter. Efficient and effective use of these materials as soil conditioners also provides one of the best means we have for maintaining and restoring soil productivity. The beneficial effects of organic wastes on soil physical properties as evidenced by increased water infiltration, water-holding capacity, water content, aeration and permeability, soil aggregation and rooting depth, and by decreased soil crusting, bulk density, and runoff and erosion are well known.

Crop residues are produced in large quantities in India and have uses in agriculture, industry, and energy. India produces over 686 Mt of crop residue annually, of which 368 Mt originates from cereal crops (Hiloidhari *et al.* 2014). Rice and wheat are the two most important cereal crops, accounting for roughly 154 and 131 Mt, respectively, of the total production of crop residues (Kumar *et al.* 2023). It has been demonstrated that adding organic residues to soils increases soil aggregation, SOC, pH, and available nutrients, among other aspects of soil fertility. It has been demonstrated that the biochemical composition of organic residues, including N, the C/N ratio, lignin, and polyphenols, largely controls the mineralization of these residues and the release of plant nutrients. In addition to crop residues, oil extraction mills also produce oilcakes as a by-product. They have significant concentrations of P and K in addition to N. For the majority of oilcakes, which mineralize easily, the C/N ratio is relatively narrow (3–15), with roughly 50–80% of the N becoming available in two to three months. Animal waste can also be used as a source of nutrients, energy, and organic matter. This material is recycled for use in agriculture in many countries, where it is used as a soil conditioner and a source of plant nutrients.

Manures and compost

Farmyard manure (FYM) and composts are well known as soil amendments made from decayed organic materials and contains significant amount of plant nutrients, which vary widely depending upon the sources. Although FYM typically have less than 1% N, P, and K, composting can concentrate this amount. Nitrogen content in manures can be improved by combining manures with bedding materials soaked in urine. Manure increased soil nutrients, SOC, and pH significantly, which had an impact on yields by raising the amount of organic N in the soil. According to Sarker *et al.* (2018), it provides the microbial community with a more stoichiometrically balanced source of nutrients (C:N ratio, microelements). This can stimulate a variety of enzyme-mediated microbial processes and encourage microbial growth and diversity, which can improve many soil physicochemical properties (Schlegel *et al.* 2017). Average chemical compositions of different manures are presented in Table 1.

Table 1. Average chemical compositions of different manures

Manure/Residue	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Rice straw	0.5–0.8	0.07–0.12	1.4–2.0
Wheat Straw	0.4–0.6	0.07–0.10	0.9–1.2
FYM	0.8–1.2	0.2–0.4	0.35–0.65
Compost	1.5–2.0	0.4	1.2
Sheep and goat manure	3.0	0.4	1.7
Poultry manure	2.5–3.0	1.13	0.7–1.2
Oil cakes	2.5–7.9	0.3–1.3	1.0–1.8
Green manure (*Sesbania*)	1.7–2.8	0.1–0.2	1.1–1.5
Azolla	1.96–5.30	0.16–1.59	0.37–5.97

Biochar as nutrients

Biochar has emerged as a potential fertilizer and soil amendment to transform agricultural practices and contribute to environmental sustainability. Biochar is a carbon-rich material produced through thermal decomposition (pyrolysis) of biomass at high temperatures and limited oxygen conditions (Mukherjee and Lal, 2014). Applications of biochar have been shown to enhance soil fertility, increase crop productivity, improve nutrient and water use efficiency, and reduce nitrous oxide (N_2O) emissions. Biochar has been marketed as a technology for long-term C storage in soils, with the goal of mitigating climate change. It has been demonstrated that it can sorb a wide range of organic and inorganic contaminants, showing promise for the treatment of water and the remediation of contaminated soils. Furthermore, compared to other organic amendments, biochar's high stability allows its positive effects on soil quality to persist over extended periods. It can act as a liming agent and also contribute to climate mitigation by sequestering C for long-term benefits (Balusamy *et al*., 2025). It improves soil nutrient retention, reducing N leaching by 10-40%, enhancing P availability by 15-50%, and K by 20-60%, making more nutrients available to crops (Sharma *et al*., 2025). It also enhances the population of beneficial microbes and stabilizes organic matter, thereby enhancing nutrient cycling and crop response to fertilizers. Similarly, biochar can raise soil pH, reduce aluminium toxicity, and improve the availability of P and micronutrients (Glaser *et al*., 2002).

Biochar can be made from a wide range of organic sources at varying temperatures with limited or absence of oxygen. Biochar is highly porous and has a high CEC. This means it can "grab" and hold onto essential nutrients like N, P, and K, releasing them slowly to plants over time. According to reports, when applied as a soil amendment, biochar can retain both cationic and anionic solutes such as phosphates, ammonium, and nitrates (Clough *et al.* 2013). Because of the biochar's sorption, soil treated with biochar exhibited decreased mean cumulative nitrate and nitrite leaching (Mukherjee *et al.* 2014). Because of the special qualities of biochar, it offers notable benefits as a soil conditioner, but it is inherently deficient in essential plant nutrients. Owing to its favourable physicochemical properties, it serves as a base material for producing slow-release fertilizers and can enhance nutrient content and overall nutrient use efficiency (NUE) through improved nutrient fixation, stability, and slow-release properties (Zhou *et al*., 2021). Numerous techniques, primarily impregnation, encapsulation, co-pyrolysis, in-situ pyrolysis, and granulation, are suggested to increase the fertilizer efficiency of biochar. Furthermore, using it *in-situ* and granulated forms, it reduces transportation and application costs while enabling customizable and efficient nutrient loading for precision and targeted delivery (Ye *et al*., 2019). Moreover, these methods minimize nutrient losses and environmental impacts, thereby improving soil health (Kim *et al*., 2014). Biochar-based fertilizers can be applied to degraded soils and high-value crops to improve soil fertility.

Recycling of waste and by-products

Compost and digested products produced by anaerobic food waste digestion and aerobic solid composting, respectively can be utilized as nutrient sources and soil amendments. Due to their abundance and the potential for low-cost, mass-production, food waste fertilizers can be a more affordable source of nutrients than commercial inorganic fertilizer sources like urea and DAP. Food wastes can be turned into fertilizers through a few different processes, including chemical hydrolysis, pyrolysis, anaerobic digestion, composting, and dehydration. Major nutrient contents in food-waste derived products (Table 2) showed that these wastes and by-products can be used as nutrient sources.

Low-grade minerals as nutrient source

For commercial production of P-fertilizers like single superphosphate (SSP), diammonium phosphate (DAP), nitro-phosphates *etc*., the raw material is essentially come from rock phosphate (RP), a finite mineral resource. It is estimated that the recoverable global RP reserves of all types and grades are estimated to be about 60,000 Mt (van Kauwenbergh, 2010). There is a general consensus that the quality and accessibility of RP reserves are decreasing, while the demand for additional P and low P-use efficiency ($<15\%$, PUE) created a doomsday scenario worldwide. Further, the peak P, showing the global consumption of P since beginning of the industrial revolution and

Table 2. Major nutrient contents of food waste-derived products used as a nutrient source and soil amendment

Products/Waste materials	C (%)	N (%)	P (%)	K (%)	S (%)	C: N	References
Composted fish food waste	38.3	1.14	0.26	0.31	-	33.6	Radziemska *et al.* (2019)
Composted market waste	45.9	1.81	0.31	2.21	-	25.3	Jara-Samaniego *et al.* (2017)
Composted catering waste	49.6	1.90	0.05	0.79	-	26.1	Farrell and Jones (2010)
Dehydrated food waste	42.0	2.00	0.10	5.00	-	21.0	Wang *et al.* (2017)
Dehydrated municipal solid waste	17.0	1.63	2.04	0.71	0.25	10.4	He *et al.* (1995)
Digested food waste	-	0.18	0.05	0.04	0.04	-	Pitts (2019)

into future years, reveals that based on consumption and supply, it is estimated that the peak P production will occur in 2030 and complete P depletion by 2150, if no action is taken for recovering P from alternative sources (Cordell *et al*., 2009). If, 60% of the current P consumption can offset through recovery or loss prevention, the Peak P can be delayed by several decades and complete P depletion can potentially be avoided.

Total phosphate resource in India is estimated to be 260 Mt, and the recoverable phosphate reserves are of the order of 142 Mt. Most of the deposits of Indian RPs are low-grade (<20%) and unsuitable for manufacturing of commercial P-fertilizers because of their low P content and low reactivity (Narayanasamy and Biswas, 1998). For manufacturing P-fertilizers, India imports large amounts of high-grade RP (>30% P_2O_5) from the countries like Egypt, Peru, Jordan and Morocco. It is estimated that the consumption of P_2O_5 was ~8.3 Mt in India, while the total production was in the order of only 4.88 Mt during the year 2023-24 (FAI, 2024). In order to bridge the wide gap between production and consumption, enhancing PUE is highly desirable. Under such circumstances, utilization of the large reserves of low-grade RP through improved fertilizer production technology, use of non-conventional source of P and maximization of applied P recovery through development of new fertilizer materials of higher PUE are of prime importance.

Situation in case of potassium is even worse as the entire requirement of K is imported in the form of either muriate of potash or sulphate of potash which require lot of foreign exchange because K-rich minerals are not available in India. India is fortunate in having the world's largest deposit of mica containing 8-10% K_2O. According to Indian Minerals Year Book (IBM, 2019), the total mica deposits in India are about 635302 tonnes of which major share are found in Andhra Pradesh (40%), followed by Rajasthan (27%), Odisha (17%), Maharashtra (13%), Bihar (2%) and Jharkhand (1%). Of the total mica mined, 75% is wasted and dumped near the mica mines. However, the waste mica can be used as a source of K if modified by chemical and biological interventions which holds a lot of promise (Biswas *et al*., 2009).

There are other low-grade mineral sources which can be effectively used as K-fertilizers. Like P, there is a wide variation regarding nutrient contents and solubility of K among different K sources. Natural sources of potassium sulphate and potassium magnesium sulphate (langbeinite) contain a significant amount of K with a higher water solubility, and they can be used as source of K. Whereas silicate minerals like greensand (glauconite), feldspar, granite and micas contain a lower K with less solubility as compared to the above salts (Basak *et al*., 2017). Clean glauconite contains up to 11% K_2O, while glauconite-rich greensands contain commonly 5%–9% K_2O. Despite a wide difference, these sources can be used in agriculture considering the prevalent soil conditions and crop requirements. The silicate minerals like mica (Basak and Biswas, 2012), feldspar, granite and greensand have been used as sources of K in several studies (Basak *et al.,* 2017), and found even more effective than chemical fertilizers in highly weathered soils. A number of rock dusts and powders are occasionally used as a source of secondary and micronutrients, which are reported in isolation from local agronomic trials. Due to limited natural availability these materials have been used by the local people, but universal recommendation and practical utility of them remain a matter of question. The release of nutrients from these mineral powders can be increased if applied along with manures in the agricultural system (Chaudhary *et al.* 2011). A number of studies have presented the ability of different K-bearing silicate minerals to yield nutrients under laboratory, pot, and field trial conditions (Table 3). The most commonly trialled minerals include granite, glauconite, phlogopite, biotite, gneiss, feldspar, *etc*.

Table 3. Summary of crop trials with direct application of silicate minerals used as K fertilizer

Mica mineral	Crop	Experiment	Agronomic benefit	Reference
Phlogopite	Rice	Pot culture	Increased grain yield	Weerasuriya *et al*. (1993)
Glauconitics andstone	Pearl millet	Sand culture	Dry matter yield K content significantly increased	Rao and Rao (1999)
	Olive	Hydroponics	Effect as slow release K fertilizer	Karimi *et al*. (2012)
Biotite	Italian ryegrass	Pot culture	Significant improvement in yield under biotite and nepheline as compared to K feldspar	Bakken *et al*. (1997)
	Timothy grass	Field	K uptake under biotite at par with KCl application	Bakken *et al*. (2000)
	Grape	Field	Increase berry yield and K content	Stamford *et al.* (2011)
	Leek	Pot culture	Biotite found most effective and readily available source of K	Mohammed *et al.* (2014)
Waste mica	Spring barley	Sand culture	Plant biomass and K uptake increased	Madaras *et al*. (2013)

Bio-activation of silicate minerals

There are some microorganisms present in soil which are able to solubilize unavailable form of K-bearing minerals to bring the K into available form. These microorganisms are able to solubilize 'unavailable' forms of K-bearing minerals, such as micas, illite, and orthoclase, by excreting organic acids, which either directly dissolves rock K or chelating silicon ions to bring the K into solution. These microorganisms are commonly known as potassium-solubilizing microorganisms (KSM), mainly bacteria and some fungi are considered as K-solubilizer and widely known as K-solubilizing bacteria (KSB) or K-dissolving bacteria or silicate-dissolving bacteria. Some research has been made about the use of K-dissolving bacteria, known as biological K-biofertilizer (Basak *et al*., 2022). The principal mechanism of K solubilization involves low molecular acid produced by the KSB. The protons associated with organic acid molecules decrease the pH of the solution and, therefore, induce the releasing capacity of cations such as Fe, K and Mg. Many workers opined that the production of carboxylic acids and capsular polysaccharide or extracellular polysaccharides and enzymes are thought to accelerate the dissolution of a variety of silicates by the application of KSM namely, *Bacillus mucilaginosus* and *Bacillus edaphicus* (Lin *et al*., 2002; Basak and Biswas, 2009). There are still very few work reported about KSB as compared to N-fixer and P-solubilizer. It was found earlier that the application of mica alone did not respond well but bio-activation with KSB was found promising as a source of K for plant (Biswas and Basak, 2014). Some of the recent findings indicate that the treatment of soil as well as mica minerals with KSB inoculation significantly increases soil K as well as plant growth (Basak *et al.*, 2017).

Application of mica alone as the source of K was not very effective in increasing the crop growth and nutrition. But an integrated application of these mineral with KSM was found promising in increasing the crop growth and yield under both pot culture and field experiments using a range of K-bearing silicate minerals in combination with either different species of KSM or composting. Some of the studies have focused on the ability of different mica minerals inoculated with KSM as an alternative source of K for crop nutrition under pot and field conditions. Here, some of the most important experiments are summarized (Table 4) in which mica materials inoculated with KSM have been used as a source of K-fertilizer. These trials include pot and field experiments, using mica minerals, for different species of KSM under various crop species.

Table 4. Summary of the experiment: Improved plant nutrition through bio intervention of silicate minerals

Mica minerals	Bio-intervention	Experiment	Salient outcomes	Reference
Biotite	Inoculation of mycorrhizal fungi (*Paxillus involutus* and *Suillus variegatus*)	Pine under pot culture	Improved K uptake by releasing K from mineral structure	Wallander and Wickman (1999)
	Inoculation with local rhizobacterial strain (K-31, K-81)	Wheat underfield condition	Improved grain yield and K status of soil	Mikhailouskaya and Tchernysh (2005)
Muscovite	Inoculation with KSB (*Bacillusmucilaginosus*)	Groundnut under pot culture	Yield and oil content increased while K status in soil improved	Sugumaran and Janarthanam (2007)
	Inoculation with local rhizobacterial strain (K-31, K-81)	Wheat underfield condition	Improved grain yield and K status of soil	Mikhailouskaya and Tchernysh (2005)
Wastemica	Inoculation with KSB (*Bacillus mucilaginosus*)	Sudan grass under pot culture	Improved biomass yields and K uptake by Sudan grass and soil K status	Basak and Biswas (2009)
	Co-inoculation of *Bacillus mucilaginosus* (KSB) and *Azotobacter chroococcum* (N-fixer)	Sudan grass under potculture	Biomass yield, K and N uptake increased	Basak and Biswas (2010)
	Inoculation with KSB (*Bacillus pseudomycoides*)	Tea plant	Significantly increased K availability in soil and K uptake by plant	Pramanik *et al.* (2019)
	Composting	Potato-soybean under field condition	Mica enriched compost significantly increased yield and K uptake by both the crops	Biswas (2011)
	Composting	Soybean under field condition	Mica charged compost improved soybean yield and K uptake as compared to ordinary compost	Meena and Biswas (2013)

Development of low-cost technology to prepare RP enriched compost (Organo-mineral fertilizer)

Large quantities of crop residues are burnt, particularly in northern India. Burning of residues poses air pollution, greenhouse gasses (GHGs) emissions, loss of carbon, nutrients, soil biodiversity and soil health deterioration. Entire amount of C, 80-90% of N, 25% of P, 20% of K, and 50% of S are lost upon burning. One tonne of rice residue contains about 400 kg of C, 5-7 kg N, 1.0-1.7 kg P, 15-25 kg K and 1.1-1.4 kg S in addition to significant amount of micronutrients. Crop residues could be recycled to the field by converting them into value added product through composting. In this respect development of value-added composts or enriched composts or organo-mineral fertilizers using crop residue along with low-grade RP and waste mica holds a lot of promise. Preparation and use of enriched compost has become an important component of sustainable agriculture and received much interest in recent years as a means of alternative utilization of crop residues and low-grade minerals like RP by composting technology, thus reducing the ill effects of residue burning as well as improving the P content (Biswas and Narayanasamy, 2006).

There has been little direct study on the composition of P that had been solubilized during composting. Reddy (2007) who applied low-grade RP to the litter of soybean showed that ~71-92% of the total solubilized P was converted to organic P. While changes in C and N forms have been reported, evidence for changing forms of P during the compost period is more circumstantial. For example, Biswas *et al.* (2009) described some changes in P during decomposition. An increase in total P content over time was proportional to the loss in organic matter during decomposition. Water soluble P (WSP) significantly increased when composting was done without RP, but decreased during composting with RP. Moharana and Biswas (2016) reported that the ordinary compost of different substrates contained lower citrate soluble P (CSP) than RP enriched composts. This may be attributed due to contribution of more P from RP in enriched composts. During the decomposition of organic residues, the microbial population increases and hence there is more demand for P. These microorganisms can assimilate the labile form of P and release it when they die. Moreover, the organic acids released during decomposition can increase the H^+ activity and make the P in RP more soluble. It was also found that RP enriched compost had more of the total P and CSP compared to ordinary composts. The P soluble in citric acid increased significantly during initial composting with RP but after 60 days citric acid soluble P decreased. Various possible reasons might explain this observation which include some form of precipitation/sorption reaction of soluble P with RP components. Initially there was an increase in soluble P, which later converted to di and tri-calcium phosphates that were citric acid soluble when *Aspergillus awamori* was grown in a medium with RP as the only source of P (Mishra *et al.,* 1984). Different fractionations of phosphorus in various RP-charged compost prepared using rice straw inoculated with and without *Aspergillus awamori* which was reported by Biswas and Narayanasamy (2002). In vitro studies with *A. awamori* also revealed that after a certain period of incubation citric acid soluble P also decreased and was converted into a citric acid insoluble apatite form (Biswas and Narayanasamy, 2006). Biswas *et al.* (2009) and Moharana and Biswas (2016) reported that Olsen-P content increased up to 90 days of composting and thereafter, decreased up to 120 days in all the composts using various substrates. This indicates that 90 days of composting is optimum for plant use as far as its availability of phosphate is concerned.

The nature of the substrate plays a major role in the composting process as well as nutrient mineralization. Moharana and Biswas (2016) was studied the amounts of release of P during the composting process of different substrates enriched with RP. It is evident that at the end of 120 days of composting, the highest WSP (0.104%) was recorded in rice straw compost, followed by chickpea stover (0.096%), wheat straw (0.091%), mustard stover (0.085%) and the lowest in tree leaves compost (0.073%). The WSP fraction at 120 days of composting varied from 3.5 to 4.5% of the total P in all the composts. The amount of CISP varied from 0.80 to 1.13% during different composting period which comprised of 32.7–54.0% of total P with different raw materials, the highest content being found in tree leaves and lowest in rice straw. At the end of composting, the highest CSP was found in the RP enriched compost of rice straw (1.53%), followed by wheat straw (1.35%), chickpea stover (1.27%), mustard stover (1.16%) and tree leaves (0.89%). Summary of experiments involving utilization of rock phosphate by composting technology are presented in Table 5.

Challenges and limitations

The current fertilizer market is dominated by the conventional fertilizer products. The non-conventional sources of nutrient materials discussed here holds immense potential to change the face of agriculture production and make it more sustainable. The scarcity of raw materials for

Table 5. Summary of experiments involving utilization of rock phosphate by composting technology

RP	Compost substrate	Observation	References
Jhabua, Mussoorie, Purulia, Udaipur	Rice straw	RP along with *Aspergillus awamori* to crop residue during composting helped to enhance the mobilization of unavailable P in RP to available forms of P. Inoculation with *A. awamori* into the composting mass increased the content of total P (2.35%) as well as WSP (0.05% P) and CSP (0.85% P) significantly.	Biswas and Narayanasamy (2006)
Udaipur	Rice straw, mustard stover and tree leaves	Olsen-P content increased up to 90 days of composting and thereafter, decreased till the end of 120 days in all the composts, indicating that 90 days of composting is optimum for its P availability for plant use.	Moharana *et al*. (2015)
Udaipur	Rice straw, wheat straw, chickpea stover, mustard stover and tree leaves	Highest CSP was found in the RP enriched compost of rice straw (1.53%), followed by wheat straw (1.35%), chickpea stover (1.27%), mustard stover (1.16%), and tree leaves (0.89%).	Moharana and Biswas (2016)
Jhabua, Hirapur	Soybean leaflitter	Decomposition of soybean leaf litter has the potential to solubilize P from insoluble low-grade RPs. It mobilized P to the extent of 20.2% of total P within 2-months.	Reddy (2007)
Lalitpur	Post-methanation bio-sludge	Laboratory study revealed that 1-month incubation was long enough to produce good quality organic P fertilizers having higher WSP, lower C/P ratio, higher population of PSM, and higher phosphatase activity in comparison to biogas sludge.	Shrivastava *et al.* (2011)
Togo	Poultry manure	Co-application of RP with manure could be a low cost means of improving the solubility of natural RP and improve their agronomic effectiveness.	Agyin-Birikorang *et al*. (2007)

manufacturing of conventional fertilizers, particularly phosphatic and potassic fertilizers are the major force to divert the resources towards the production and investment for alternate, non-conventional and innovative sources of nutrients. The various alternate P sources like direct application of low-grade RPs, the nano-based RPs or P-fertilizers, the nano-clay polymer composite loaded materials, use of low molecular weight organic acids for P solubilization, use of phosphate solubilizing bacteria for solubilizing the native recalcitrant P sources have been evaluated by various researchers for their potential to conventional P-fertilizer. Similarly, use of different K sources like waste mica through enriched compost preparation, low grade silicate mineral powders (*e.g.*, feldspar, greensand) (Basak *et al.* 2023), potash derived from molasses can be very effective alternate K-fertilizer source. However, the work related to these products are at smaller scale limited to field studies and laboratory studies, while for launching the fertilizer materials more robust approach is required. The various challenges and limitations in the path of developing the new fertilizer material needs further development.

The alternate or non-conventional materials generally will be without subsidy as it will be mostly prepared from indigenous resources. However, initial investment costs are likely to be high. Also, overnight switching to non-conventional materials will not happen as the dependence on the conventional fertilizer products is too high. The resistance from the farming community needs to be addressed in phases through lucrative credit and incentives of adopting the new non-conventional materials in the form of some "*Green Credit Programs*" as the energy consumption for the alternate fertilizers will be less. One silver lining in this direction is the use of indigenous materials through the "*Atma Nirbhar Bharat*" initiative which aims to build a self-reliant nation. The initiative of utilizing potash derived from molasses from sugar industries for manufacture of potassic fertilizer is a novel initiative by the Government. Through this, the fertilizer industry aims to manufacture 10-12 lakh metric tonnes of K-fertilizer (14.5% K content) and provide an alternate to costly MOP. Such new initiatives also demand collaboration between the researchers and the industry. Since the introduction and marketing of new fertilizer materials at commercial scale involves lot of financial implications, focused initiative and collaboration between the apex agriculture research organizations i.e. ICAR, the fertilizer industry and its own R&D section along with the Central Government is essentially needed.

Despite the benefits, the shift is not without hurdles. Unlike chemical fertilizers, which provide an instant "green-up," non-conventional sources take time to rebuild soil fertility and they are slow in their initial results. They are labour intensive processes. For example, preparing on-farm inputs like compost or fermented sprays requires more labour compared to buying a bag of fertilizer. Further, there exists wide gap as effective use of biofertilizers requires understanding soil pH, moisture, and temperature—factors that demand better extension services and training. Non-conventional nutrient sources are the bedrock of the next agricultural revolution of green agriculture in India. By moving away from "chemical-intensive" to "knowledge-intensive" farming, India can achieve a truly Green Agriculture one that is productive, profitable, and permanent. The integration of traditional wisdom with modern science offers a roadmap for a self-reliant and climate-resilient Bharat.

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Perspective on Water–Food–Energy Nexus of Green Regenerative Rice–Wheat Systems in the Indo-Gangetic Plains of India

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ABSTRACT

The Water–Food–Energy (WFE) nexus provides an integrated framework for understanding the interlinkages among water use, food production, and energy consumption in agricultural systems. In India, these interconnections are particularly evident in the rice–wheat cropping system (RWCS) of the Indo-Gangetic Plains (IGP), which forms the backbone of national food security but faces growing sustainability challenges due to groundwater depletion, high energy dependence, soil degradation, and climate variability. This review synthesizes existing literature to examine how regenerative agriculture can operationalize the WFE nexus in RWCS. Evidence indicates that regenerative practices such as reduced tillage, residue retention, and improved irrigation management enhance irrigation water productivity, energy-use efficiency, soil organic carbon stocks, and greenhouse gas mitigation, while maintaining crop yields. The review highlights key synergies and trade-offs and emphasizes that regenerative agriculture offers a viable pathway toward climate-resilient and resource-efficient agricultural development in the Indo-Gangetic Plains.

Key words: Water use, Energy, Crop production, Regenerative agriculture, Sustainability

Introduction

The Water–Food–Energy (WFE) nexus highlights the intrinsic interdependence of water security, food production, and energy use three pillars essential for sustainable development. Agriculture lies at the center of this nexus, as food production is both water- and energy-intensive, while farming practices strongly influence water availability, energy demand, and environmental outcomes (Bhatt *et al*. 2016; Fagodiya *et al*. 2023). Sector-specific interventions often create unintended consequences across other domains, underscoring the need for integrated resource management.

In India, the relevance of the WFE nexus is particularly pronounced in the Indo-Gangetic Plains (IGP), where irrigated agriculture dominates livelihoods and food production. The rice–wheat cropping system (RWCS), a legacy of the Green Revolution, has ensured food security but at the cost of intensive groundwater extraction, rising energy consumption, and declining soil health (Benbi 2018). These pressures raise serious concerns about the long-term sustainability of the system.

Regenerative agriculture (RA) has emerged as a promising alternative paradigm that seeks to restore ecological processes while sustaining productivity. By emphasizing reduced soil disturbance, residue retention, improved water management, and enhanced biological processes, RA has the potential to reshape WFE interactions in RWCS (Lal 2015; Meena *et al*. 2023). This review synthesizes existing evidence to assess how regenerative practices influence water, energy, and soil dynamics in the IGP through a WFE nexus lens.

Conceptual Framework of the WFE Nexus in RWCS

In rice–wheat systems, irrigation water demand largely determines energy use for pumping, while soil health mediates water retention, nutrient cycling, and crop resilience. Conventional practices characterized by puddled transplanted rice and intensive tillage result in high irrigation requirements and energy consumption. Degraded soil structure further reduces water-use efficiency, reinforcing negative feedbacks within the WFE nexus.

Regenerative agriculture modifies these linkages by improving soil structure and increasing soil organic carbon, which enhances infiltration and moisture retention. Reduced irrigation demand directly lowers energy consumption, while improved nutrient cycling reduces dependence on synthetic fertilizers and their associated embodied energy (Pathak *et al*. 2020). These changes generate positive feedbacks across the WFE nexus, improving system efficiency and environmental performance.

Water, Energy, and Soil Dimensions in the Indo-Gangetic Plains

Water and Energy Use

Conventional RWCS in the IGP is among the most water- and energy-intensive agricultural systems globally. Prolonged flooding in rice cultivation leads to excessive groundwater abstraction, particularly in Punjab and Haryana, resulting in declining water tables and increasing energy demand for pumping (Benbi 2018). High dependence on subsidized electricity and diesel further exacerbates energy inefficiency.

Evidence from field studies indicates that regenerative practices such as Direct-Seeded Rice (DSR), Alternate Wetting and Drying (AWD), and residue mulching can reduce irrigation demand by 25–35% while improving irrigation water productivity (Pathak *et al*. 2020; Fagodiya *et al*. 2023). Reduced irrigation requirements translate directly into lower energy consumption, highlighting strong water–energy synergies within the nexus framework.

Soil Health and Carbon Dynamics

Soil degradation and declining soil organic carbon (SOC) stocks are major constraints under conventional RWCS management. Intensive tillage, residue removal, and imbalanced fertilizer use reduce soil structure and biological activity (Bhatt *et al*. 2016). In contrast, regenerative practices promote SOC accumulation and soil restoration.

Long-term experiments across the IGP report SOC increases of approximately 0.2 to 0.4% yr{ ^{1} under regenerative management (Lal 2015; Meena *et al*. 2023). Increased SOC enhances nutrient retention, water-holding capacity, and yield stability, while also contributing to greenhouse gas mitigation through carbon sequestration.

Synthesis of WFE Nexus Outcomes

The comparative analysis in Table 1 demonstrates that regenerative rice–wheat cropping systems (RWCS) offer clear advantages over conventional practices across key Water–Food–Energy (WFE) nexus dimensions in the Indo-Gangetic Plains. Regenerative systems substantially reduce irrigation requirements, thereby alleviating pressure on groundwater resources, while simultaneously

Table 1. Comparative Water–Food–Energy nexus outcomes of conventional and regenerative rice–wheat systems in the Indo-Gangetic Plains

Dimension	Indicator	Conventional RWCS	Regenerative RWCS	Key implication
Water	Irrigation requirement	High (≈1700–1900 mm yr^{-1})	Reduced (≈1200–1400 mm yr^{-1})	Lower groundwater stress
Energy	Energy-use efficiency	Low–moderate	Higher	Reduced fossil-fuel dependence
Soil	Soil organic carbon	Declining or stable	Increasing (0.2–0.4% yr^{-1})	Improved soil resilience
Climate	GHG footprint	Higher	Lower	Climate-mitigation co-benefits
Food	Crop productivity	Input-dependent	Stable	Sustainable yield maintenance

Synthesized from Bhatt *et al*. (2016), Benbi (2018), Pathak *et al*. (2020), Meena *et al*. (2023), and Fagodiya *et al*. (2023).

improving energy-use efficiency and lowering dependence on fossil fuels. Increases in soil organic carbon under regenerative management enhance soil resilience and contribute to long-term system stability. These improvements are accompanied by a reduced greenhouse gas footprint, indicating important climate-mitigation co-benefits. Crucially, these environmental gains are achieved without compromising crop productivity, which remains stable rather than input-intensive. Overall, the table highlights regenerative RWCS as a more resource-efficient, climate-smart, and sustainable pathway for maintaining food security in the Indo-Gangetic Plains.

Nexus Synergies and Trade-offs

A WFE nexus perspective reveals strong synergies under regenerative agriculture. Reduced irrigation demand lowers energy consumption and associated emissions, while improved soil health enhances water and nutrient-use efficiency. These co-benefits demonstrate that productivity and resource conservation can be mutually reinforcing rather than conflicting.

However, transitional challenges remain, including initial investment costs, knowledge gaps, and short-term yield variability during adoption. Addressing these barriers requires supportive institutional mechanisms and targeted extension efforts to enable farmers to adopt regenerative practices without undue risk.

Conclusions

This review demonstrates that regenerative agriculture provides a viable green pathway to address Water–Food–Energy nexus challenges in the Indo-Gangetic Plains. While conventional rice–wheat systems have historically ensured food security, they have also imposed significant water, energy, and environmental costs. Regenerative practices enhance irrigation efficiency, reduce energy dependence, restore soil carbon, and lower greenhouse gas emissions without compromising productivity.

By aligning ecological restoration with economic viability, regenerative agriculture operationalizes the WFE nexus and supports climate-resilient agricultural development. Scaling these practices will require coherent policy support, institutional coordination, and sustained capacity building. A nexus-based approach can ensure that the Indo-Gangetic Plains continue to feed the nation while safeguarding the natural resource base on which their productivity depends.

Advancing future research in this area will require spatially explicit assessments of WFE trade-offs across alternative climate and policy pathways, supported by the integration of field observations, remote sensing, and process-based models. Scaling regenerative agriculture will depend on stronger carbon accounting systems, rigorous economic valuation of ecosystem services, and participatory policy frameworks. With effective implementation, regenerative agriculture can underpin India's move toward a resilient, low-emission, and resource-efficient agricultural future, allowing the Indo-Gangetic Plains to meet national food demands while maintaining the ecological integrity essential for sustained productivity.

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Role of Resource Conservation Technologies for Green Agriculture: An Agrophysical Perspective

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ABSTRACT

Indian agriculture must simultaneously feed a growing population, sustain rural livelihoods and reduce its environmental footprint under growing constraints of water, land, energy and climate. The country hosts nearly one-fifth of the world's population but only a small fraction of its freshwater. Agriculture already uses most of this water and large areas are degrading. Against this backdrop, resource conservation technologies (RCTs) such as conservation agriculture, laser land levelling, micro-irrigation, alternate wetting and drying in rice, site-specific nutrient management and Happy Seeder-based residue management offer practical options to 'produce more from less'. This article views RCTs through an agrophysical lens, treating them as deliberate interventions in the soil-plant-atmosphere continuum. By improving soil structure, enhancing infiltration and water storage, reducing soil evaporation and enhancing crop transpiration, and moderating microclimates, RCTs can stabilise or increase yields while saving water, energy and nutrients and reducing greenhouse gas emissions. Evidence from long-term experiments and on-farm trials across India shows substantial gains in water productivity, profitability and resilience. Yet adoption remains uneven, constrained by context-specific performance, knowledge and capacity gaps, weak service ecosystems and fragmented policies. The article argues that innovations in agrophysical measurement, modelling and digital tools, combined with stronger partnerships across disciplines, are central to designing, targeting and scaling RCT packages for truly green agriculture in India.

Key words: Soil-Plant-atmosphere continuum, Resource use efficiency, Agrophysics, Climate-resilience, Indian smallholder systems

Introduction

Indian agriculture today stands at a crossroads. It still provides livelihoods to around 40% of the workforce, while contributing about 16-18% of national GDP (GOI, 2024). This imbalance points to a deeper reality. Food and nutrition security, rural employment and a large share of export earnings continue to depend on a sector that must now operate under tightening constraints of water, land, energy and climate (Pathak, 2023).

These constraints are structural, not temporary. India hosts nearly 18% of the global population but only about 4% of global freshwater resources, and agriculture uses close to 80% of annual water (World bank, 2023). Groundwater now irrigates well over half of India's irrigated area, making the country the world's largest groundwater user, with around 60% of irrigated farming dependent on groundwater withdrawals (CGWB, 2023). At the same time, nearly one-third of the geographical area shows signs of land degradation, according to recent assessments based on the Desertification and Land Degradation Atlas of India (MoEFCC, 2023). Soil organic carbon levels are low in many regions, and fertiliser use is often imbalanced, with nitrogen heavily over-applied relative to phosphorus and potassium. Climate change adds another layer of uncertainty through more frequent droughts, intense rainfall events and heatwaves, which interact with small and fragmented landholdings to amplify risk at farm level.

Against this backdrop, ‘green agriculture’ is not a slogan but a necessity. Here the term is used in a practical sense – production systems that deliver food and fibre with higher resource-use efficiency, lower environmental footprints and greater resilience, while remaining economically viable for farmers. Achieving this requires more than incremental improvements in single inputs. It calls for a rethinking of how we manage the soil-plant-atmosphere continuum (SPAC) so that water, energy and nutrients are channelled into productive pathways and away from losses. This is precisely where resource conservation technologies (RCTs) and agrophysics intersect.

A rich family of RCTs has emerged in Indian agriculture over the past two decades. Examples include conservation tillage and residue retention, laser land levelling, raised beds, drip and sprinkler irrigation, alternate wetting and drying (AWD) in rice, site-specific nutrient management (SSNM), integrated nutrient management (INM), residue-managing machinery such as the Happy Seeder, and a range of digital and sensing tools. Synthesis of global and South Asian evidence shows that conservation agriculture (CA)-based RCTs can improve soil organic carbon, soil structure and water holding capacity, and reduce evaporation losses (Abdallah, 2021). Evaluations of micro-irrigation in India similarly report substantial water savings and yield gains across vegetables, fruit crops and sugarcane, often with improved profitability (IIM-Ahmedabad, 2020).

The central argument of this article is that these technologies are best understood not as isolated gadgets but as physics-based interventions that intentionally modify the movement and storage of water, heat and mass in the field. Agrophysics provides the language, measurements and models to describe these changes; from bulk density, porosity and hydraulic conductivity in the soil profile, to evapotranspiration, canopy temperature and greenhouse gas fluxes above the surface. It also offers a way to connect plot-scale experiments with watershed and basin-scale questions that matter for groundwater security, river flows, air quality and climate commitments.

The article first summarises resource constraints and sustainability challenges in Indian agriculture (Section 2), and then outlines a simple typology of RCTs relevant to Indian conditions (Section 3). It then explains the agrophysics behind RCTs (how they reshape the SPAC; Section 4). Section 5 highlights evidence of impacts under Indian conditions. Challenges, knowledge gaps and the way forward are placed in Section 7, arguing that the main barriers to scaling RCTs are no longer only technical. They lie equally in knowledge systems, service ecosystems and policy incentives. It concludes that innovations in agrophysics, through smarter measurement, modelling and co-design with farmers, can play a central role in moving RCTs from scattered success stories to mainstream practice in Indian agriculture.

Resource constraints and sustainability challenges in Indian agriculture

Indian agriculture still supports a large share of the population, but the natural resource base that sustains it is under stress. Water, soil, land and energy are all becoming limiting, while climate variability is increasing and farms are getting smaller and more fragile.

Water stress and groundwater depletion

Per capita renewable freshwater availability in India is already close to the water-stress threshold, and agriculture uses around 80% of total withdrawals. Groundwater now irrigates more than half of the country's irrigated area, making India the world's largest groundwater user. In several states, extraction exceeds annual recharge and hundreds of assessment units are officially classified as 'over-exploited' (CGWB, 2024).

Electricity-subsidised pumping has been a lifeline for farmers but also locks agriculture into high energy use and creates pressure on state power utilities. Climate projections suggest that in some parts of north India, groundwater recharge may decline due to changes in monsoon rainfall and temperature, adding to long-term risk.

Land degradation and poor soil health

Remote-sensing indicate that about 30% of total geographical area of India is undergoing land degradation (SAC, 2021). Much of this lies in dryland climatic zones where soils are vulnerable to erosion, crusting and nutrient depletion. Accelerated erosion on sloping lands, wind erosion in arid and semi-arid zones, and waterlogging and salinisation in some canal commands all contribute.

Average SOC of Indian soils is ~0.54% (Das *et al*., 2022), while in several intensively cultivated states (Punjab, Haryana etc.), SOC has declined to about 0.2-0.4% (Meena *et al*., 2021) This is far below a practical target of 1–2% SOC, desirable for good structure and water-holding capacity in most mineral soils (Pawar *et al*., 2017). Analyses of Soil Health Card data show widespread deficiencies in organic carbon and available nitrogen, along with emerging imbalances in phosphorus, potassium and secondary nutrients in several states. Low SOC translates directly into poorer aggregation, more compaction, lower infiltration and a reduced ability to buffer droughts and intense rainfall events.

Nutrient imbalance, energy use and emissions

While fertiliser use has grown substantially, it is often imbalanced. The agronomically desirable N:P:K consumption ratio of around 4:2:1 has been exceeded in many states, with nitrogen applied at much higher relative rates than phosphorus and especially potassium, leading to nutrient imbalances and lower overall fertiliser-use efficiency (GOI, 2024; FAI, 2023).

Agriculture is also a significant contributor to India's greenhouse gas emissions, mainly through enteric fermentation, rice cultivation, fertiliser use and manure management. Crop residue burning wastes valuable organic matter and produces large pulses of particulate matter and greenhouse gases. The concentration of rice residue burning in parts of the Indo-Gangetic Plains leads to episodes of severe air pollution in northern India almost every winter. At the same time, agricultural electricity use for groundwater pumping has grown rapidly, adding to the sector's carbon footprint and financial stress on utilities.

Small farms and climate risk

Most operational holdings in India are small and marginal, with average farm size a little above one hectare and declining. Smallholders have limited capacity to invest in irrigation, soil improvement or mechanisation, even when technologies are available.

Climate change increases this vulnerability. Many districts now experience more frequent extreme rainfall, droughts, heat waves and floods. These shocks interact with groundwater depletion, land degradation and input-price volatility, creating a complex risk environment for farmers. Against this backdrop, technologies that save water and energy, protect soil, and stabilise yields are not optional, they are essential.

Concept and typology of resource conservation technologies

A wide range of RCTs has emerged in India over the last two decades. In simple terms, an RCT is any field practice, machine or decision tool that helps produce ‘more from less’, i.e., more output per unit of water, energy and nutrient, and with lower environmental impact.

From an agrophysical perspective, RCTs work by changing the way water, heat and mass move through the SPAC. They deliberately modify surface conditions, soil structure, rooting patterns and microclimate so that a greater share of water and nutrients is captured and used productively by crops, and a smaller share is lost as runoff, deep drainage, evaporation or emissions.

Table 1. Groups major RCTs into five overlapping categories

1. Conservation agriculture (CA): Reduced/ zero tillage, residue retention and diversified rotations.
2. Precision land and water management: Laser land levelling, raised beds, improved surface irrigation, drip, sprinkler and methods like AWD in rice.
3. Soil health and nutrient management: Site-specific nutrient management (SSNM), integrated nutrient management (INM), organics, residue recycling and carbon-building practices.
4. Climate-smart mechanisation: Zero-till drills, Happy Seeder and related residue-managing machinery, energy-efficient implements and solar-powered pumping.
5. Digital, sensing and decision-support tools: Soil moisture sensors, micro-meteorological stations, remote sensing, and mobile or web-based advisories that translate measurements into on-farm decisions.

In practice, technologies are adopted in packages. For example, laser levelling with zero-till wheat and residue retention, or drip irrigation with fertigation and plastic mulching. In Indian conditions, CA-based practices such as zero-till wheat after rice and in-situ residue management have shown clear benefits in terms of timeliness of sowing, reduced costs and improved soil structure. Laser land levelling and micro-irrigation have delivered large water savings and yield gains in rice-wheat systems and high-value crops. Site-specific nutrient management tools, together with integrated nutrient management, have improved fertiliser-use efficiency and reduced the emission intensity of grains. Climate-smart mechanisation and digital tools then knit these elements together into practical packages for farmers.

Agrophysics behind resource conservation technologies

RCTs make sense when we look at them through the lens of the SPAC. Below is a comparison of SPAC under conventional management and RCT-based management practices (Fig. 1).

Conventional management

In a conventional field, repeated tillage, residue removal or burning, and inefficient surface irrigation often create (a) surface sealing and compact layers, which reduce infiltration and encourage runoff and waterlogging; (b) high soil evaporation, especially when the soil is left bare between rows or after sowing; (c) uneven water distribution, with some patches over-irrigated and others under-irrigated, especially when fields are poorly levelled; and (d) unfavourable temperature and aeration, with hot bare soil surfaces, prolonged saturation in low spots, and restricted root growth.

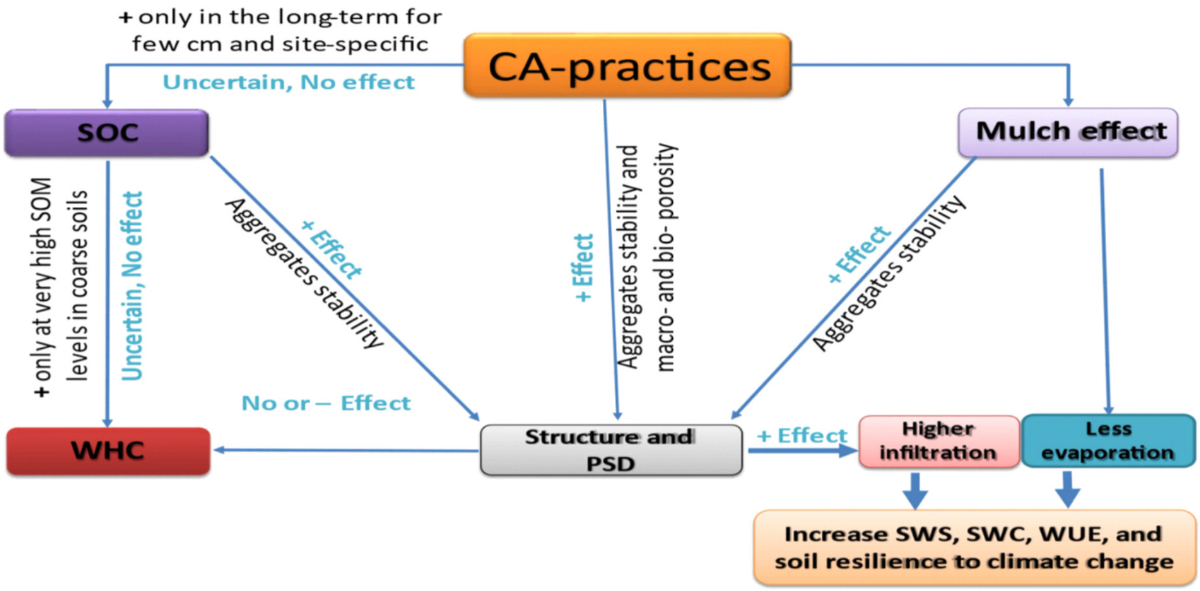

Fig. 1. Flowchart illustrating how conservation agriculture practices contribute to improved soil organic carbon (SOC), soil structure and pore system, water holding capacity (WHC), and soil water content and storage (SWC, SWS) [Source: Abdallah *et al.*, 2021]

In Fig. 1 (left panel), this appears as strong arrows for runoff, deep percolation and evaporation, shallow rooting and a compacted soil profile. High inputs of water and energy are needed to maintain yields in such systems.

RCT-based management

Under RCTs (Fig. 1; right panel), key aspects of the SPAC change. For example,

1. Better structure and infiltration

Reduced tillage, residue cover and organic inputs help rebuild soil organic matter and aggregation. Bulk density decreases slightly, macroporosity increases and infiltration improves. Laser levelling and raised beds further guide water movement. More of the rainfall or irrigation enters and stays in the root zone, and less is lost quickly as runoff or deep drainage.

2. Improved soil water storage and plant-available water

Higher organic matter and better structure shift the soil water retention curve so that more water is held in the range available to plants. Mulch slows evaporation and protects the surface. The root zone acts like a more efficient “sponge”: it fills quickly when water is available and releases water slowly to plants between events.

3. More transpiration, less evaporation

Residues and mulches shade the soil and reduce direct soil evaporation. Precision irrigation methods deliver water where roots are, rather than wetting the whole surface. As a result, a greater share of total evapotranspiration passes through the plant (transpiration), which is the part actually linked to biomass production.

4. Moderated microclimate and better aeration

Covered soils are cooler in the day and less prone to extremes. Raised beds and better drainage reduce the duration of saturation around roots. Canopy development over a more favourable root zone can reduce canopy temperature during hot periods. Together, this improves crop resilience to heat and short dry spells.

5. Improved gas exchange and reduced emissions

Less tillage and residue retention reduce CO_2 pulses from soil disturbance. Practices like AWD in rice shorten periods of anaerobic soil conditions and reduce CH_4 formation. Better matching of water and nitrogen reduces 'hot spots' for N_2O production.

Measuring and modelling the changes

Agrophysics provides 'tools' to measure these changes -soil bulk density, infiltration, hydraulic conductivity, soil water retention, soil moisture profiles, ET components, soil temperature and gas fluxes. Micro-meteorological towers, sensors and remote sensing extend these measurements across time and space. It also provides 'models' that simulate water balance, energy balance and crop growth under different RCT combinations. These models help researchers and planners answer "what if" questions: for example, what happens to water use and yield if laser levelling, zero tillage and AWD are combined across a canal command? In short, agrophysics explains why RCTs work and helps design and target them better.

Taken together, these examples show that RCTs are better understood as physics-based interventions in the SPAC than as isolated 'gadgets'. Fig. 2 summarises this logic by linking major RCT families (Table 2) to key agrophysical processes and, in turn, to water, soil, energy and climate outcomes that define green agriculture in India.

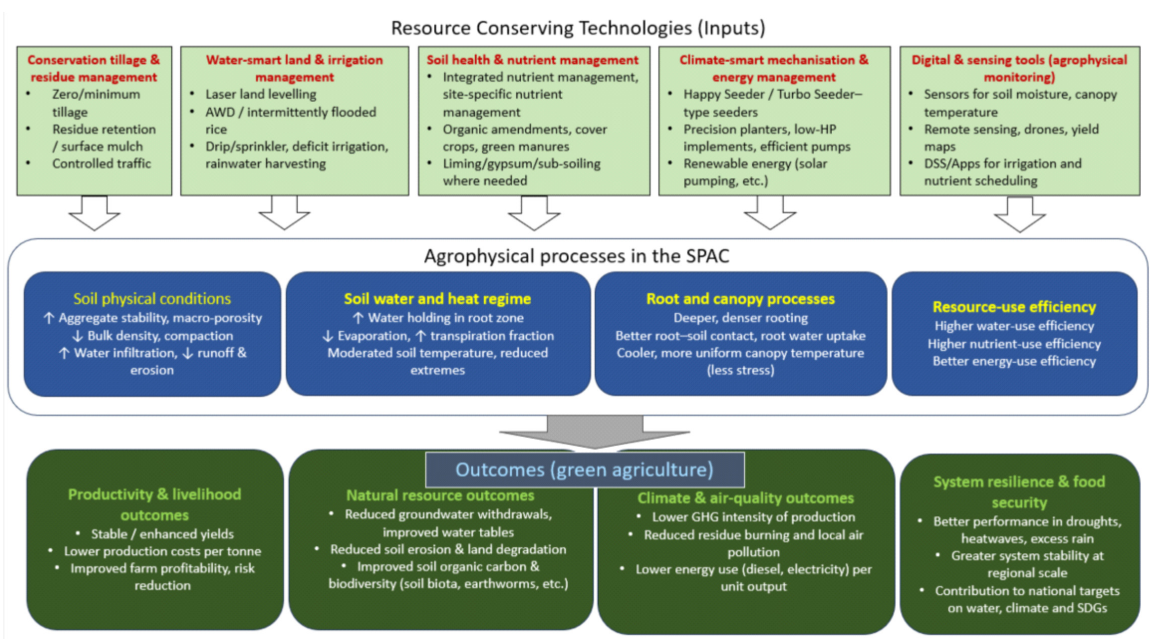

Fig. 2. Agrophysics-informed framework linking resource conservation technologies (RCTs) to green agriculture outcomes in India

Table 2. Major categories of resource conservation technologies (RCTs), key examples, resources conserved and agrophysical basis

RCT category	Technologies/ Practices	Primary resources conserved	Key agrophysical processes/ Principles	Indian systems/ Regions
Conservation agriculture	Zero/minimum tillage, residue retention, diversified rotations	Soil, water, energy, carbon	Reduced soil disturbance; improved aggregation; surface cover moderating soil temperature and evaporation; reduced runoff and erosion	Rice–wheat (IGP); maize–/cotton–wheat; rainfed cereal–pulse systems (central & peninsular India)
Precision land & water management	Laser land levelling; raised beds/FIRB; furrow irrigation; drip/ sprinkler; AWD in rice	Water, energy, labour	Uniform field slope; controlled infiltration and percolation; improved water distribution and application efficiency	Canal command areas; groundwater-irrigated regions
Soil health & nutrient management	SSNM, INM, organics, biochar	Nutrients, carbon, water	Better soil structure and porosity; enhanced water-holding capacity reduced nutrient leaching and volatilizaion	Rainfed and irrigated systems, horticulture
Climate-smart mechanization & energy	Happy Seeder; turbo seeders; residue mulchers/ shredders; energy-efficient tractors; solar pumps	Energy, labour, time, crop residues	Optimized traction and draft; residue anchoring and distribution; fewer field operations; timely sowing	Mechanised cereal systems in NW and central India; CHS for smallholders in several states
Digital, sensing & DSS tools	Soil moisture sensors; micro-met; satellite/ UAV remote sensing; IoT nodes; mobile apps AI/ML-based DSS	Water, nutrients, labour, information	Real-time measurement of soil-plant status; improved scheduling of irrigation and fertilisation	Diverse crops; high-value horticulture; pilot digital agriculture and water-stressed basin projects

Evidence of impacts

RCTs are attractive because they do not ask farmers to sacrifice yield in order to save resources. Evidence from India and South Asia shows that many RCTs can increase or stabilise yields while reducing water, energy or fertiliser use.

Water and yield

Laser land levelling reduces irrigation water use and usually increases rice and wheat yields modestly, with typical studies reporting 10-25% irrigation savings and around 5-10% yield gains in rice–wheat rotations (Aryal *et al.*, 2015). Zero-till wheat often yields more than conventional wheat because it is sown earlier and faces less terminal heat stress (Keil *et al.*, 2017). Drip-fertigated vegetables and fruit crops regularly show water savings of 40-60% and yield increases of 15-40% compared with surface-irrigated fields (Debbarma *et al.*, 2018). Subsurface drip systems in sugarcane and other wide-spaced crops save large amounts of water and improve ratoon performance. AWD in rice can reduce irrigation requirements without harming yields when implemented carefully.

Energy, costs and profitability

Zero-till wheat cuts the number and intensity of tillage operations, reducing fuel use for land preparation by roughly half or more in many studies (Laxmi *et al.*, 2007l Erenstein and Laxmi, 2008). Happy Seeder-based systems remove the need for separate residue disposal, further saving fuel and labour (CIMMYT, 2019). Laser land levelling reduces time and energy needed for irrigation (Sidhu *et al.*, 2015).

Although micro-irrigation requires upfront investment, evaluations under the PMKSY–Per Drop More Crop scheme show that benefit–cost ratios are often higher than in comparable surface-irrigated systems, especially in vegetables and fruit crops where yield and quality gains are large (IIM-Ahmedabad, 2021). SNM and INM can reduce fertiliser costs per unit of output and improve gross margins by raising yields while optimising nutrient use (Sapkota *et al.*, 2021).

Environment and resilience

RCTs also deliver important environmental benefits. Replacing residue burning with in-situ management and Happy Seeder technology cuts particulate pollution and greenhouse gas emissions from residue management while improving soil cover (CIMMYT, 2019 AWD reduces methane emissions from rice fields by roughly 30–50% in many trials (IRRI). CA and INM build soil organic carbon and improve structure, making fields more resilient to drought and intense rain. SSNM and better nitrogen management reduce nitrous oxide emissions and nitrate leaching. Table 3 summarises these impacts for some key RCTs, with indicative numerical ranges and references.

Table 3. Illustrative impacts of selected resource conservation technologies under Indian conditions (indicative ranges)

RCTs	Cropping system / region	Water saving/ water productivity*	Change in crop yield**	Energy / cost impacts	Key environmental benefits	Selected source
Laser land levelling	Rice–wheat, NW and central IGP	10–25% less irrigation water; 20–30% higher water productivity	5–10% higher rice and wheat yields; more uniform stands	15–25% lower pumping time and energy; reduced re-levelling cost, higher net returns per ha	Lower runoff and deep percolation; less nutrient loss; reduced emissions from pumping and repeated field operations	Aryal *et al.* 2015
Zero / minimum tillage wheat after puddled rice	Rice-wheat, IGP	10–20% less irrigation water (especially first irrigation); better soil moisture conservation	5–10% higher wheat yields mainly via timelier sowing	50–80% less fuel and tractor hours for land preparation; 15–25% lower land-preparation cost	Lower CO_2 emissions from fuel; better surface soil structure; enables residue retention	Erenstein & Laxmi 2008

contd...

RCTs	Cropping system / region	Water saving/ water productivity*	Change in crop yield**	Energy / cost impacts	Key environmental benefits	Selected source
Happy Seeder–based wheat with in-situ rice residues	Rice-wheat, NW India (Punjab, Haryana, W. UP)	Similar seasonal irrigation water; improved soil cover often increases water productivity compared with burn–tillage	Wheat yields maintained or 5–10% higher; better stability across years	Fewer tillage and residue-handling operations; systems typically 10–20% more profitable than residue burning	Avoids residue burning and associated PM and GHG emissions; lifecycle analyses show > 70% reduction in GHGs from systems residue management vs burning	Sidhu *et al.* 2015
Drip irrigation with fertigation in vegetables and fruit crops	Vegetables (tomato, chilli, etc.) and fruits in semi-arid & irrigated regions	40–60% less water than surface methods; 25–50% higher water productivity	15–40% higher yields; better size and quality	Lower pumping hours per unit yield; often higher fertiliser-use efficiency and better benefit–cost ratio despite initial investment	Reduced deep percolation and nutrient leaching; lower water footprint per unit produce; less weed growth when combined with mulching	Jat *et al.*, 2011
Subsurface drip fertigation in sugarcane and widely spaced crops	Sugarcane, banana etc., in southern and western India	30–35% irrigation saving vs surface / furrow irrigation; 50–65% higher water-use efficiency reported in sugarcane	10–25% higher cane and ratoon yields in SSDF vs surface irrigation	Reduced conveyance and application losses; improved fertiliser-use efficiency through fertigation	Lower risk of waterlogging and salinity; lower emissions per tonne of produce due to reduced water and energy use	Mahesh *et al.*, 2018
Alternate wetting and drying (AWD) in irrigated rice	Lowland rice in canal and tube-well commands	Up to 20–30% less irrigation water under 'safe AWD' compared with continuous flooding; higher water productivity	Grain yield usually maintained within ±5% of flooded rice when AWD implemented correctly	Lower pumping frequency and duration; reduced irrigation cost; better trafficability for mechanical harvest	30–70% lower CH_3 emissions without yield penalty; lower water table and improved redox conditions; potential to reduce As uptake	IRRI AWD factsheet
Site-specific nutrient manage-ment	DSS-based fertiliser use	Rice and wheat in several states	No direct water saving; modest improvement in water productivity via better growth	5–20% higher yields over farmers' fertiliser practice, depending on imbalance	Often 10–20% less N or P use for similar or higher yields; better gross margins above fertiliser cost. Lower N, O and leaching risks from over-application; improved nutrient balances and soil fertility when combined with organics and residue recycling	Sapkota *et al.* 2021

Challenges, knowledge gaps and way forward: role of agrophysics and innovation

The evidence in earlier sections shows that RCTs can save water and energy, improve soil health, maintain or increase yields and reduce emissions. Yet adoption across India is still uneven and often slow. The key question is why a set of technologies that works well in experiments and pilots does not spread faster on farmers' fields, and how agrophysics and innovation can help bridge this gap.

Why adoption lags behind the evidence

A first reason is that RCTs are highly context-specific. The same practice can behave very differently on different soils and under different climate and water regimes. Zero tillage with residue retention may work very well on medium-textured alluvial soils with moderate rainfall and good drainage, but can create waterlogging or pest problems on heavy clays if it is not combined with land levelling, drainage or suitable rotations. Drip irrigation and mulching can transform coarse-textured soils by boosting water-holding capacity, yet on deep loams with already good water management, the extra benefit may appear smaller to farmers. Many 'mixed' results arise because RCT packages are not sufficiently adapted to local physical conditions, not because the underlying principles are wrong.

A second reason is limitations in knowledge and capacity. In many places, RCTs are introduced as single gadgets, e.g., a Happy Seeder, a laser leveller, a drip system, rather than as part of an integrated management package. Farmers may hear that they should keep residues, reduce tillage or change irrigation timing, but not fully understand why. Extension workers, who are essential intermediaries, are usually trained in conventional agronomy and input recommendations, not in agrophysical concepts such as infiltration, soil water storage or evapotranspiration. When weeds increase after direct-seeded rice, or when soil warms more slowly under heavy residues, they may not have a clear explanation or adjustment strategy. Without a strong understanding of cause and effect, both farmers and field staff tend to revert to familiar practices.

A third constraint is access to machinery, infrastructure and services. Many RCTs require specialised machines at the time of adoption. Laser levellers, zero-till drills, Happy Seeders, raised-bed planters and micro-irrigation systems are significant investments for small and marginal farmers. Where custom hiring centres and private service providers function well, farmers can pay for services instead of owning machines, and adoption is higher. Where service ecosystems are weak, RCTs remain confined to larger farms or to project villages.

A fourth set of challenges is related to data and diagnostics. RCTs work by modifying the SPAC, but in many programmes we still track only what goes in and what comes out - hectares covered, fertiliser applied, yield harvested. Changes in bulk density, aggregate stability or hydraulic conductivity, the partitioning of ET between soil evaporation and transpiration, and root-zone development are rarely monitored outside research plots. Without good diagnostics along the continuum, it is hard to explain why a technology performs differently at two sites, or to convince farmers and policymakers about its medium- and long-term benefits.

Finally, policy and incentive structures are fragmented. Water, energy, fertiliser, residue management and climate policies are designed and implemented by different departments. Farmers may receive cheap or flat-rate electricity for pumping, encouraging heavy groundwater use, while at the same time being urged to save water. Fertiliser subsidies may keep nitrogen prices very low relative to other nutrients, even as soil test data show serious nutrient imbalances. Residue burning is discouraged, but alternatives may not be reliably available or profitable without strong service support. In this environment, signals to farmers are mixed, and RCTs compete with incentives that favour business as usual.

How agrophysics can improve the design of RCT packages

Within this complex landscape, agrophysics has a distinctive role. It cannot fix all socio-economic and institutional barriers, but it can greatly improve how RCTs are designed, targeted and explained.

On the design side, agrophysics helps move from generic recommendations to locally adapted packages. Instead of promoting 'zero tillage' in general terms, scientists can use measurements of infiltration, soil water retention and root-zone depth to specify which combination of reduced tillage, residue cover, nutrient management and land configuration is appropriate for a given soil and climate. For example, zero tillage with partial residue retention and balanced fertilisation may be recommended on a well-drained loam whereas on a heavy clay, the same package might be modified to include raised beds, shallow drainage or sub-soiling at intervals. By building these recommendations on physical measurements and models, agrophysicists can assemble technology bundles that are robust for local conditions rather than being designed for an average that exists nowhere in reality.

Agrophysics also encourages thinking in terms of whole systems. It makes it clear that a laser leveller is not only a land-shaping machine; it is a tool to change micro-relief, water ponding, flow paths and infiltration patterns. A residue-managing seeder is not just a drill; it is an instrument for anchoring residue, reducing raindrop impact and shading the soil surface. Drip irrigation is not only a water-saving device; it is a way to control the spatial pattern of soil wetting and drying in the root zone. This systems view helps combine technologies in ways that reinforce each other rather than work at cross purposes.

Agrophysics as an evidence engine and diagnostic tool

Beyond design, agrophysics provides quantitative evidence of how and why RCTs work. Infiltration and runoff measurements under conventional and RCT plots can show how quickly water enters the soil and how much is lost as surface flow. Soil moisture profiles over time can demonstrate that a given practice maintains plant-available water for longer between rainfall or irrigation events. Measurements of bulk density and aggregate stability can document improvements in structure, which can then be linked to root penetration and root length density. Micro-meteorological measurements can separate soil evaporation from transpiration and show how residue cover shifts the balance towards more productive use of water. Gas-flux measurements can track changes in CH_4 emissions under AWD, or N_2O emissions under improved nitrogen and water management. When such results are presented clearly, they make the invisible visible. They show farmers and extension workers that a technology is not magic, but a predictable way of changing water and energy flows in the field. They allow policymakers to compare technologies not only in terms of yield but also in terms of water saved per kg of grain, emissions avoided per hectare, or reduction in the probability of crop failure in a dry or hot year. This kind of evidence is essential if RCTs are to be embedded in water, climate and air-quality strategies, and not treated only as agronomic curiosities.

Diagnostics are equally important in the field. Agrophysical indicators such as simple infiltration tests, penetration resistance, soil moisture at key depths or canopy temperature at midday can serve as early warnings that something is wrong with the way an RCT is being implemented. For example, if soil under a residue-retaining system shows increasing penetration resistance and poor infiltration, it may signal that traffic is not controlled and compaction is building up. If canopy temperatures under drip irrigation are repeatedly higher than in neighbouring fields at the same stage, irrigation scheduling may be inadequate. Integrating such diagnostics into extension and farmer training can turn RCTs from fixed recipes into adaptive management strategies.

Innovation in measurement, digital tools and modelling

The classical instruments of agrophysics like infiltrometers, tensiometers, TDR probes, lysimeters, micro-meteorological towers are essential at research stations, but they can be too complex or expensive for routine use in farmers' fields. Innovation is needed to bridge this gap.

One direction is to use high-precision methods to calibrate simpler, low-cost tools. Once the relationship between soil water tension and easily readable tensiometer values is established for a given soil, extension workers can use tensiometers in farmers' fields to guide irrigation without needing full laboratory retention curves. Once the link between residue cover percentage and evaporation reduction is quantified, simple field charts or smartphone applications can help farmers judge whether they have enough surface cover. Low-cost sensors for soil moisture, canopy temperature or groundwater level, if properly validated, can be powerful aids to RCTs management and scaling.

Digital agriculture multiplies these opportunities, but only if it is anchored in sound physical understanding. Decision-support systems that recommend when and how much to irrigate, or how to distribute nitrogen over time, must be based on realistic water balance models, crop coefficients and soil properties, adjusted with local data. Remote-sensing products that estimate ET or crop water status bring valuable spatial coverage, but they should be interpreted using ground measurements and basic physics, not treated as opaque outputs. In this sense, agrophysics provides the backbone for digital tools, ensuring that advisories are not only convenient but also reliable and transferable.

Modelling is another area where innovation can greatly support RCT scaling. Field-scale crop-soil-water models can simulate how different RCT combinations perform across years with different weather. When coupled with hydrological models, they can extend this analysis to watersheds and river basins, exploring questions such as how widespread adoption of micro-irrigation and conservation agriculture could influence groundwater recharge, canal efficiencies or river flows. These models allow exploration of "what if" scenarios that would be too risky or expensive to test directly, and can inform decisions on where and how to prioritise RCT promotion.

A way forward centred on agrophysics

Looking ahead, the way forward lies in a closer partnership between agrophysics, agronomy, engineering, social sciences and policy. For researchers, this means designing long-term experiments and on-farm trials that focus on realistic bundles of practices, not single interventions, and that measure changes in key physical indicators alongside yields and incomes. For extension systems, it means investing in training that builds a basic understanding of how soil, water and energy flows respond to different RCTs, so that field staff can diagnose and solve problems rather than only delivering standard messages.

For machinery and service ecosystems, agrophysical insights can help specify what kind of equipment is most needed in which environments. Say, where controlled traffic is more important than deep tillage, or where raised beds will offer the biggest gains. For policy, robust physical evidence on water savings, emission reductions and resilience benefits can justify aligning incentives so that RCTs contribute directly to water-security, climate and air-quality targets.

Fig. 3 summarises this logic in a three-panel framework: challenges at farm, landscape and system levels feed into core agrophysical and innovation functions, which in turn generate field, resource and policy outcomes. The arrows highlight not only the forward flow from challenge to solution, but also the feedback loops through monitoring and learning that are essential for adaptive scaling of RCTs. In simple terms, the challenge is to make the "physics of the field" visible and usable for everyone involved in agricultural decisions. When farmers can see how water actually moves in their soils under different practices, when extension workers can read soil and crop indicators with confidence, and when planners can quantify how RCTs change water and energy balances at scale, adoption will become faster and more durable. Agrophysics, supported by appropriate innovation in tools and institutions, is central to this process and to making resource conservation technologies a normal part of green agriculture in India, rather than a collection of promising but scattered success stories.

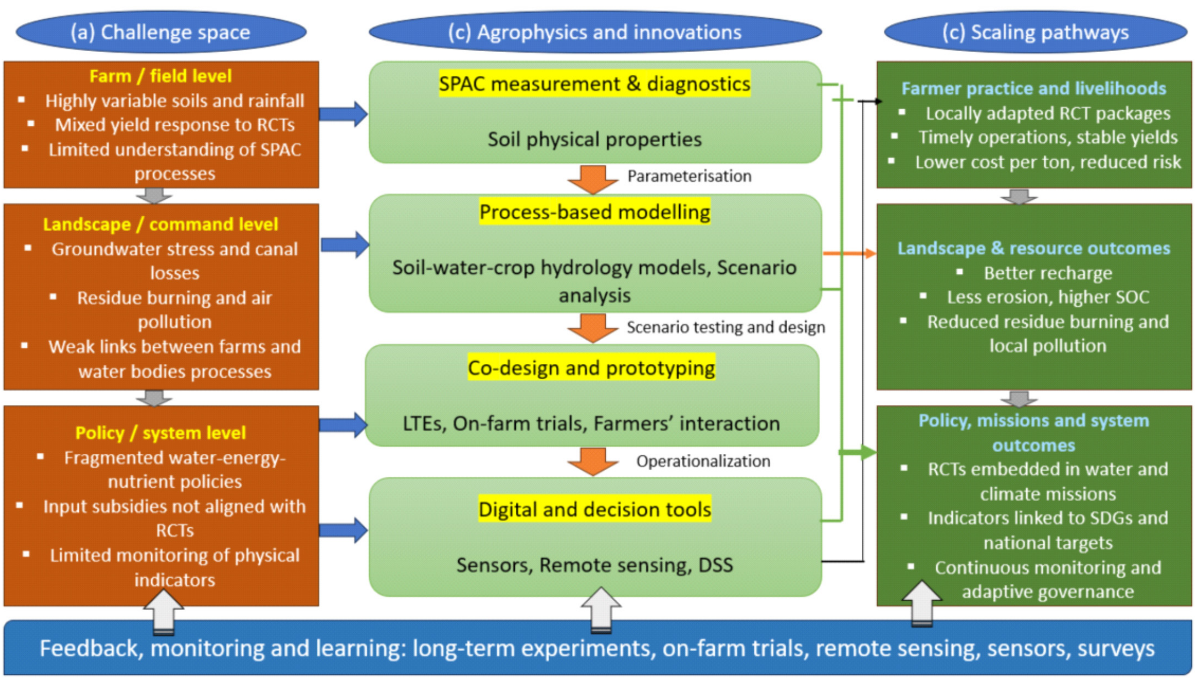

Fig. 3. Agrophysics-centred framework for scaling resource conservation technologies (RCTs)

Conclusion

Indian agriculture is facing rising demand, shrinking and degraded natural resources and a more variable climate. Simply pushing more water, energy and fertiliser through conventional systems will not deliver the kind of 'green agriculture' India needs. Resource conservation technologies demonstrate that it is possible to improve or stabilise yields while saving water, energy and nutrients and lowering emissions. The physics behind these technologies is clear. They alter the way water, heat and mass move through the SPAC.

The key challenge now is not to prove that RCTs can work, but to make them work reliably and profitably for many more farmers, across diverse agroecologies. This requires treating RCTs as locally adapted packages rather than isolated gadgets, supported by strong service ecosystems, clear economic incentives and coherent policies. Agrophysics has a central role in this transition. By measuring how soils, crops and microclimates respond to different practices, by turning those measurements into simple indicators and decision rules, and by linking field-scale processes to landscape- and basin-scale outcomes, agrophysics can help India move from *ad hoc* success stories to systematic, large-scale adoption of resource conservation technologies.

For the Indian Society of Agrophysics, this is both a scientific and a strategic opportunity. By positioning agrophysics at the heart of RCT design, targeting and monitoring, the community can help shape the next generation of innovations for water-smart, climate-resilient, low-emission agriculture. Done well, this will not only conserve resources but also secure livelihoods, improve air and water quality and bring India closer to its broader goals for a greener, more resilient agricultural future.

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National Seminar on Innovations in Agrophysics for Green Agriculture
22-24 January 2026 at ICAR-IIWM, Bhubaneswar

Drones and Artificial Intelligence for Green Agriculture

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ABSTRACT

The growing demand for sustainable food production has intensified the need for integrating advanced digital technologies into agriculture. Drones, also known as Unmanned Aerial Vehicle (UAVs) and Artificial Intelligence (AI) have emerged as transformative tools in achieving green and precision agriculture, enabling efficient resource management, reduced environmental impact, and improved productivity. This paper examines the synergistic role of drones and AI in promoting environmentally sustainable farming systems. Drone-based remote sensing, mapping, and variable-rate applications facilitate real-time monitoring of crop and soil conditions, while AI-driven analytics support predictive modeling, disease detection, and data-based decision-making. Together, these technologies enable precise input management—optimizing water, fertilizer, and pesticide use—and enhance crop health assessment, yield prediction, and soil restoration. Moreover, upscaling of these technologies to larger areas, especially in heterogeneous land use scenarios, using satellite remote sensing provides valuable insights to farmers to facilitate timely decisions on site-specific input applications. The space-borne data gets supplemented by drone based remote sensing platforms, which have made a significant breakthrough in the operational delivery of important crop traits. The real-time estimation of the important crop and soil health indicators through the integration of drone imagery, AI, and edge computing enables precise input application for improving crop yield. The paper also highlights case studies in soil health assessment, crop growth monitoring, and precision spraying, emphasizing their contribution to sustainable and climate-resilient agriculture. A few results achieved through these technologies developed under ICAR – NePPA (Network Program on Precision Agriculture) and implemented in the research farm of ICAR – Indian Agricultural Research Institute and many other places, have also been discussed further to provide a comprehensive understanding. Finally, future perspectives on AI–drone integration underscore their potential to build intelligent, automated, and low-carbon farming systems aligned with the global goals of green and smart agriculture.

Keywords: Artificial intelligence, Green agriculture, Drones, Unmanned aerial vehicles (UAVs), Remote sensing, Edge computing, Precision agriculture

Introduction

The global agricultural sector faces the dual challenge of ensuring food security while minimizing environmental degradation. Precision farming, also known as smart or digital agriculture, integrates advanced tools—such as sensors, drones, AI, and IoT—to optimize input use and increase productivity. When combined with green technologies, this approach minimizes greenhouse gas emissions, reduces chemical runoff, and promotes sustainable resource use. Green technologies in agriculture include renewable energy integration, biofertilizers, biodegradable crop protection agents, and water-efficient irrigation systems. Together, precision farming and green technology enhance efficiency and sustainability across the soil–plant–atmosphere continuum, aligning agricultural growth with ecological preservation (Kaur *et al.*, 2025; Micheni *et al.*, 2022).

Precision agriculture (PA) leverages data-driven technologies to facilitate real-time monitoring of crop and soil conditions, enhance productivity and reduce environmental impact. Recent advances in Artificial Intelligence (AI) have significantly accelerated PA by enabling real-time data analysis, support predictive modeling, and automated decision-making (Espinel *et al*. 2024). Among these, edge computing, machine learning regression, Generative AI (Gen-AI), Deep Convolutional Generative Adversarial Networks (DCGANs), Predictive and Prescriptive AI are emerging as pivotal tools in advancing scalable and intelligent agricultural systems. Edge computing enables data processing at or near the data source—such as on drones/ UAVs, tractors, or field sensors—minimizing latency and reducing reliance on cloud infrastructure. This is particularly advantageous in rural areas with limited connectivity, enabling timely responses to field conditions. Concurrently, Gen-AI models, particularly DCGANs, have demonstrated efficacy in generating synthetic, high-resolution crop imagery to augment training datasets, address data scarcity, and enhance model generalization for crop classification and trait estimation. Remote sensing technologies, including drones and satellites, provide critical multispectral and hyperspectral data for estimating crop biophysical parameters such as leaf area index (LAI), leaf nitrogen content (LNC), leaf chlorophyll content (LCC), and canopy chlorophyll content (CCC) (Venkata *et al*. 2025). The UAVs can be frequently used to acquire high-resolution images at a field scale, with the capacity to provide crop trait estimates with very high spatial variability. They play a vital role in identifying plant stress, growth stages, disease infestation, photosynthetic activity, yield, and nutrient cycling (Yang *et al*. 2015). Integrating AI with these platforms facilitates high-resolution monitoring across both spatial and temporal scales. AI-enabled fusion of UAV and satellite data has shown enhanced accuracy in trait estimation under diverse environmental conditions. The reflectance spectroscopy from crops reveals a strong relationship with major crop traits (Aasen *et al*., 2018). Therefore, it is very critical to analyze the spectral responses from crops collected through different remote sensor platforms. Though these approaches have their benefits, they also come with method-specific shortcomings that could be overcome by using a hybrid approach (Verrelst *et al*. 2013). In hybrid approaches, simulated spectra and corresponding variable values from process-based radiative transfer models as high-quality training data for ML methods—a hybrid method can be developed that is reliable, robust, and highly efficient in estimating crop health parameters. The operational delivery of crop traits from these hybrid models using Google Earth Engine (GEE) revolutionized the storage, processing, and extraction of critical information from remote sensing data. Its ability to handle large datasets over extensive areas in minutes and deliver results in near real-time through a simple browser interface makes it an ideal platform for such applications.

In this study, the main objective is to examine the potential of integrating drone technology and artificial intelligence (AI) within the framework of green and precision agriculture, to analyze different applications of Drones and AI in Precision agriculture, including technologies for precision agriculture and understanding future of Drones and AI in agriculture. Ultimately, the goal is to present a comprehensive understanding of how the synergy between drones and AI can drive the transition toward intelligent, low-carbon, and climate-resilient agricultural systems that align with the global vision of sustainable food production.

Technologies for Precision Agriculture

Precision agriculture relies on a suite of interconnected technologies that collectively measure, analyze, and respond to on-farm variability with high accuracy. Sensors and Internet of Things

(IoT) devices continuously monitor key soil and environmental parameters such as moisture, pH, temperature, and nutrient levels, providing real-time data critical for informed decision-making. These ground-based observations are spatially complemented by Global Positioning System (GPS) and Geographic Information System (GIS) technologies, which enable detailed spatial mapping and site-specific management of agricultural fields. Drones and Unmanned Aerial Vehicles (UAVs) further enhance this system by capturing high-resolution imagery to detect crop stress, monitor growth patterns, and identify variability across fields. The analytical backbone of precision agriculture is formed by Artificial Intelligence (AI), which processes large and complex datasets to generate predictive insights and decision-support models. These outputs are integrated into Decision Support Systems (DSS) that help farmers optimize input use based on data from multiple sources. Additionally, Variable Rate Technology (VRT) applies this information in real time to adjust irrigation, fertilizer, and pesticide distribution according to field-specific needs. By synchronizing these technologies, precision agriculture minimizes resource wastage, enhances yield precision, and promotes environmental stewardship through efficient and sustainable farm management.

Drone Technology

Drone stands for Dynamic remotely operated navigation equipment and it is an unmanned aircraft, formally known as Unmanned Aerial Vehicle (UAV). Drone may be considered as a robot which is remotely controlled using software generated flight plans in association with mounted sensors and external GPS (Global Positioning System). These aerial platforms are designed to perform various agricultural operations through advanced sensing and imaging technologies. These systems are typically equipped with high-resolution cameras, multispectral and hyperspectral sensors, and payload modules that allow data collection across spatial, temporal, and spectral dimensions. In precision agriculture, drones play a critical role in bridging the information gap between field conditions and management decisions. By capturing real-time data on crop health, soil variability, and environmental parameters, they enable farmers to make informed, site-specific interventions. The portability, flexibility, and ability of drones to access difficult terrains make them valuable tools for both large-scale commercial farms and smallholder operations, ensuring efficient, data-driven, and sustainable agricultural management.

According to Food and Agricultural Organisation of United Nations, "The adoption of modern technologies in agriculture, such as the use of drones or unmanned aerial vehicles (UAVs) can significantly enhance risk and damage assessments and revolutionize the way we prepare for and respond to disasters that affect the livelihoods of vulnerable farmers and fishers and the country's food security."

Potential Uses of Drone Technology in Agriculture

Surveillance and Mapping: Drones generate high-resolution field maps for detecting soil variability and crop growth attributes. This enables precise identification of nutrient deficiencies, water stress, and pest and diseases infested zones for site specific interventions.

Input Application: UAVs equipped with sprayers enable precision spraying of fertilizers, herbicides, and pesticides. Drone has potential to be use as Variable Rate Technology for site specific input application, enhancing input use efficiency.

Seed Broadcasting and Transplanting: Autonomous drones can distribute seeds or perform precision planting in targeted areas which allow for uniform seed distribution and rapid planting, even in areas where manual labor is limited or terrain is challenging.

Fumigation: Drones safely and uniformly apply fumigants, reducing human exposure and chemical waste.

Drone-based interventions drastically reduce resource use, improve coverage efficiency, and minimize environmental impacts—key elements of green agriculture

AI in Agriculture

Artificial Intelligence is interdisciplinary field, usually regarded as a branch of computer science, dealing with models and systems for the performance of functions generally associated with human intelligence, such as reasoning and learning.

Artificial Intelligence (AI) is characterized as machine intelligence designed to emulate human-like functioning. It serves as a cognitive engine, facilitating analysis and decision-making based on data acquired from various sources.AI processes this acquired information to derive meaningful insights. This collaborative approach is evident in everyday personal devices like fitness trackers, Google Home, Amazon Alexa etc. Examples of tasks that machines equipped with artificial intelligence can undertake include, Speech recognition, Problem solving, Planning and Learning. The figure below illustrates the concept of "What constitutes Artificial Intelligence?"

Artificial Intelligence (AI) serves as the computational backbone of green and precision agriculture, enabling intelligent, data-driven decision-making for sustainable farm management. By integrating machine learning (ML), deep learning (DL), and advanced data analytics with diverse agricultural datasets, AI enhances the ability to monitor, predict, and optimize farming operations with remarkable precision. Modern agriculture generates vast volumes of heterogeneous data from satellites, Unmanned Aerial Vehicles (UAVs), Internet of Things (IoT) devices, and field-based sensors. AI algorithms process and interpret these datasets to uncover complex relationships between environmental factors, crop growth dynamics, and soil health parameters—insights that are often beyond human perception.

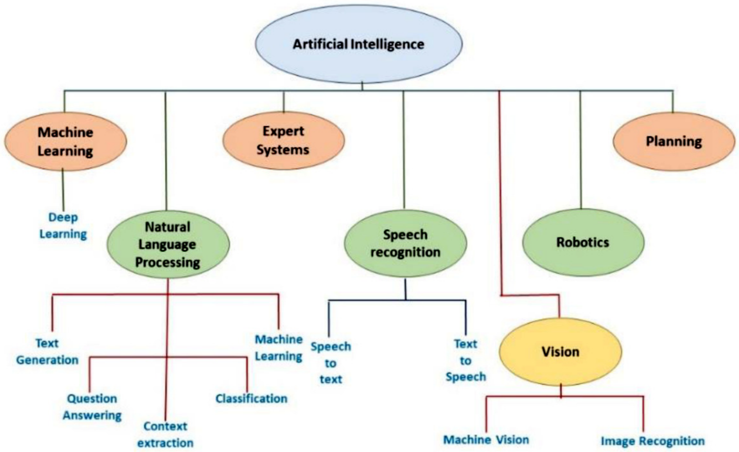

Fig. 1. Components of Artificial Intelligence

A major application of AI in agriculture is the early detection of crop stress, disease, and pest outbreaks. Through image classification and pattern recognition, deep learning models can detect subtle visual cues in leaf texture, color, or canopy structure that indicate the onset of biotic or abiotic stress. This facilitates timely interventions, minimizing yield losses and reducing dependency on chemical pesticides. Another critical use of AI lies in yield prediction and resource optimization. Predictive models analyze historical and real-time data to forecast crop yields, determine nutrient requirements, and optimize irrigation schedules, thereby ensuring that water and fertilizers are applied only when and where they are needed.

Furthermore, AI-powered decision support systems (DSS) integrate information from multiple sources—including weather data, soil conditions, and crop growth stages—to guide automated decision-making and precision interventions. Such systems enhance farmers' capacity to respond proactively to changing field conditions, improve input-use efficiency, and reduce operational costs. In addition, AI-driven robotics and automation are transforming field management by enabling autonomous machinery capable of planting, weeding, and harvesting with high precision.

By facilitating pattern recognition, predictive analytics, and resource optimization, AI contributes directly to the goals of green agriculture. It supports the reduction of greenhouse gas emissions by minimizing resource wastage and promoting site-specific input management. Moreover, AI-based systems enhance ecosystem resilience through climate-smart strategies that improve soil health, conserve biodiversity, and adapt to environmental variability. In essence, AI bridges the gap between sustainability and productivity—driving the evolution of agriculture toward a more intelligent, efficient, and ecologically responsible future. Artificial Intelligence in IoT involves embedding AI technologies, such as machine learning, deep learning, and natural language processing, into IoT devices, sensors, and platforms to enable smart decision-making, learning, and autonomous actions. It represents the integration of AI capabilities into IoT devices and systems, enabling these devices to analyze data, make decisions, and perform tasks autonomously. It aims to enhance the intelligence and efficiency of IoT deployments by leveraging AI algorithms and techniques. In terms of security, AI implements advanced measures such as anomaly detection, authentication, and authorization to safeguard IoT networks. Real-time decision-making benefits from edge computing, reducing latency in critical applications like autonomous vehicles. Natural Language Processing (NLP) and voice recognition enhance human-machine interactions, particularly in smart homes.

Drones and AI based applications for Green Agriculture

Soil Health assessment

The availability of key soil nutrients, like soil organic carbon (SOC), plant-available nitrogen (N), available phosphorus (P), and available potassium (K), serves as a significant gauge of soil fertility and its operational capability. Monitoring and assessment of these parameters are critical for maintaining and enhancing the productivity of agricultural soils. Soil sampling and subsequent laboratory analysis using chemical methods are, although very precise, time-consuming, labor-intensive and expensive. Soil analysis through spectroscopy has demonstrated itself as an expedited and reliable approach for forecasting overall soil attributes, especially in determining soil nutrients. These spectroscopic data can also be fused with multiple data sources using machine learning techniques to produce accurate digital maps of various soil properties at a high resolution scale. The potential of various spectroscopic techniques, including lab-based and airborne VIS-NIR, MIR (absorbance and emissivity), was assessed using important multivariate models for predicting various soil fertility properties. The spectroscopic data analysis revealed that the support vector machine (SVM) model outperformed the other multivariate models in predicting most of the soil properties in all four types of spectroscopies (Mondal *et al.*, 2025). Next to SVMR, other models such as random forest (RF), artificial neural network (ANN), and partial least squares regression (PLSR) also performed well in predicting various soil properties. Moreover, PLSR score-based multivariate models outperformed solo multivariate and optimized index-based models for fast and non-invasive estimation of SOC using lab-based spectroscopy (Das *et al.*, 2023). The MIR (absorbance) spectroscopy was found to be superior to other techniques. The VNIR spectroscopic data collected using portable instrument can be converted to synthetic hyperspectral imagery for accurate prediction of soil fertility parameters (Rejith *et al.*, 2025). The combined VIS-NIR-MIR spectra were unable to further improve the prediction accuracy over MIR-absorbance spectra. Many studies aimed to evaluate Mid-infrared spectroscopy (MIRS) techniques like Fourier transform infrared (FTIR) spectroscopy for rapid and accurate quantification of several soil properties utilizing the prediction power of partial least squares regression (PLSR) (Engelmann *et al.*, 2025; Lelago and Bibiso, 2022).

Different hyperspectral sensors in the VIS-NIR range mounted to ground, airborne (UAV) and satellite platforms were also evaluated for assessing soil fertility attributes at laboratory and field conditions. The sensors used were (i) Spectroradiometer (ASD) (spectral reflectance, 350-2500 nm) at laboratory and field conditions (ii) UAV mounted Headwall Nano-Hyperspec (UAV Headwall VNIR), (spectral reflectance, 400-1000 nm), (iii) UAV mounted Headwall Co-Aligned HP (UAV Headwall VNIR+SWIR), (spectral reflectance, 400-2500 nm), and (iv) ENMAP satellite data (spectral Reflectance, 400-2500 nm) (Figure 2). Spectral signatures of the soil at laboratory conditions, field conditions from spectroradiometer, from UAV-based both imaging sensors and satellite-based imaging sensors were compared for signal noise ratio and pattern. Spectral modelling using multivariate models was carried out to select the best prediction model. The lab-based proximal spectral measurements provide the best results, followed by UAV and space-borne imaging

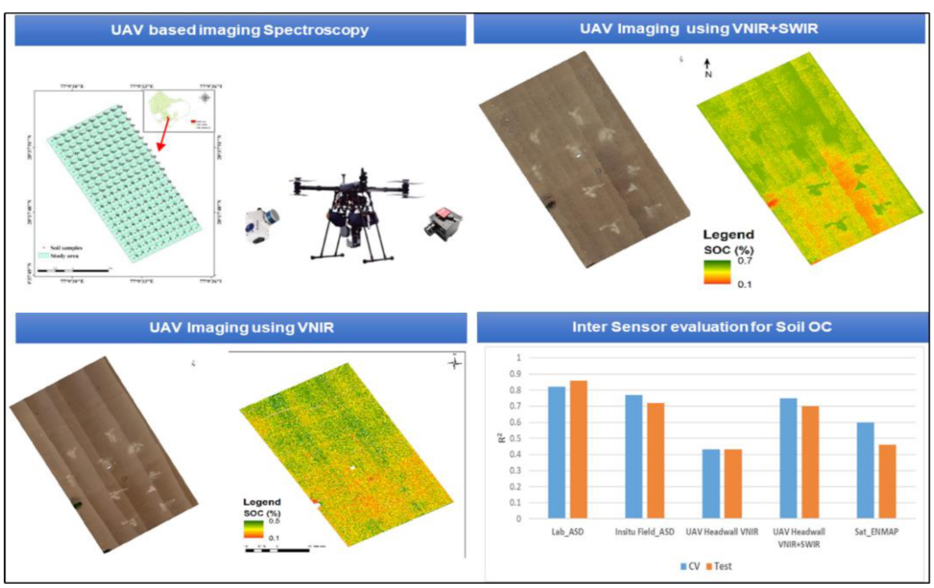

Fig. 2. UAV integrated Sensor-based Soil Fertility Assessment

spectroscopic techniques. High-resolution maps of important soil fertility indicators were generated from UAV data with the help of these prediction models, which facilitate the detection of changes in soil fertility in successive crop seasons and guide input application. Not only hyperspectral data, but also several attempts were made to generate soil prediction maps using UAV and satellite-based multispectral images with the help of multiple machine learning techniques (Tripathi *et al*., 2024).

Generation of digital soil maps for various soil fertility properties was developed using the airborne/spaceborne imaging spectroscopic data, topographic data of SRTM-DEM, vegetation indices of remotely sensed data and lab-measured soil properties data using machine learning regression techniques. Among the DEM-derived variables, slope, elevation (DEM), LS factor, aspect, analytical hill shading, total catchment area, Multi-resolution index of valley bottom flatness (MRVBF), Topographic wetness index (TWI), profile curvature, etc., were observed to be the major factors controlling the spatial distribution of those soil properties. Therefore, imaging spectroscopic data proved its efficacy in predicting and digitally mapping soil properties. The digital maps performed better than kriged maps in predicting most of the soil properties. The potential of UAV-captured images for soil fertility mapping was also carried out using spectral indices and a digital surface model (DSM) (Enriquez *et al*., 2025). Another emerging potential approach for accurate soil fertility estimations is X-ray fluorescence data in combination with machine learning regression. The stepwise Generalized Linear Model (GLM), Random Forest (RF), partial least square regression (PLSR), etc., to predict the important soil fertility properties showed great potential of X-ray data (Benedet *et al*., 2021; dos Santos *et al*., 2020). The accuracy assessment indicators revealed that the various sensor-based approach has the potential to achieve more accurate predictions, which will offer an optimized agricultural practice and insights for supporting informed decision-making.

Crop Growth Monitoring

Crop Health Monitoring using UAV imaging and Machine Learning Models

The UAV-acquired hyperspectral imagery was used for estimating important growth traits of the wheat crop using machine learning regression models. The imagery consists of 269 bands in the spectral range of 400-1000nm with a spectral interval of 2.2 nm and a spatial resolution of 4 cm. Figure 3 shows the detailed workflow consisting of major steps adopted for the retrieval of crop traits from UAV hyperspectral imagery. The spectral data and vegetation indices were used for training the ML models. The input data was subjected to dimensionality reduction to reduce the redundancy and spectral dimensionality. The partial least squares was used to reduce the spectral dimensionality of the spectral data. This is a very crucial step in regression analysis for enhancing the information content in hyperspectral bands by transforming the data into a lower dimension without any loss in information content. Multiple machine learning models were evaluated for predicting the important traits in wheat crops (Sahoo *et al*. 2023a; 2024b). The ELM outperformed other models in both calibration and validation spectral datasets, with very high R^2 values for estimating the nitrogen content. Instead of relying on spectral data directly, various spectral indices can be computed to accurately estimate different crop variables. A total of 61 and 27 vegetation indices were selected from a detailed literature review and used for estimating the leaf nitrogen content and LAI of wheat crops (Rejith *et al*. 2022; Sahoo *et al*. 2023c; Rejith *et al*. 2025). After applying suitable feature selection methods, such as Variable Importance Projection (VIP), PLS (Partial Least Squares) regression combined with the VIP (Variable Importance in the Projection),

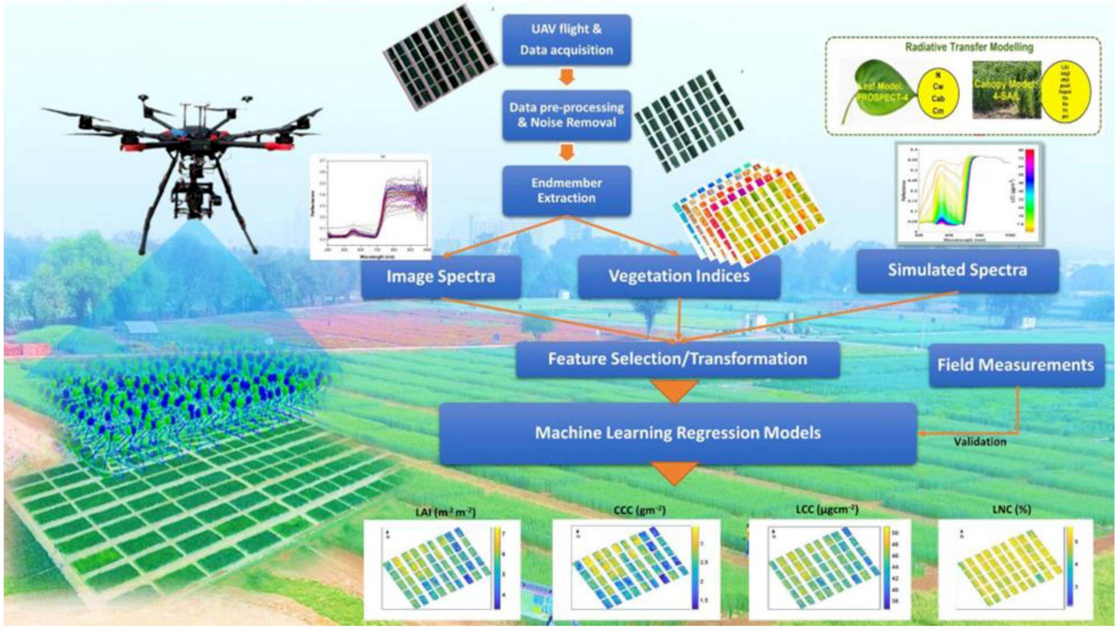

Fig. 3. Workflow showing the retrieval of crop traits from UAV hyperspectral data (modified from Sahoo *et al*. 2023b-c, Sahoo *et al*. 2024b)

R-Square (R^2), etc., twelve indices were found to be suitable for N and LAI estimation. The artificial neural network (ANN) and extreme gradient boosting (XGBoost) models optimized using these indices resulted in very good R^2 values for estimating leaf nitrogen and LAI. Finally, the optimised model was applied to the pre-processed hyperspectral imagery for generating the spatial variability maps of plant N content.

Apart from image spectra and vegetation indices, an attempt was made to generate simulated spectra using the radiative transfer model and then use these data as the input for retrieving crop traits such as LAI and CCC (Rejith *et al*. 2023; Sahoo *et al*. 2023b). The term hybrid is used to indicate the combination of a simulated input dataset and the RT model. On comparing eight different machine learning models, the GPR was found to be best with high accuracy in estimating the traits. The PCA with 20 components were used to reduce the spectral dimensionality of the data. The optimised GPR models were applied to pre-processed UAV hyperspectral data to generate spatial variability maps of mean estimates and their associated uncertainties. Figure 4 (a) shows the retrieved LCC map of wheat crops generated using the hybrid GPR model applied to the UAV hyperspectral imagery collected over the wheat crops in rabi 2021-22. Figure 4 (b) shows the scatter plot generated by validating the model using in situ measurements of LCC. The validation results indicate superior accuracy for the hybrid approach revealed from RMSE, NRMSE, MAE, and R^2 values of 7.09, 12.15%, 5.28, and 0.76, respectively. High retrieval accuracy and lower uncertainties suggest the potential of hybrid GPR models for the accurate and near-real-time retrieval of crop traits from UAV data.

Crop Health: Disease and pest

Hopper burn, induced by brown planthopper (BPH, *Nilaparvata lugens*) are significant challenge to rice production in India. A detailed study on characterizing the spectral reflectance collected

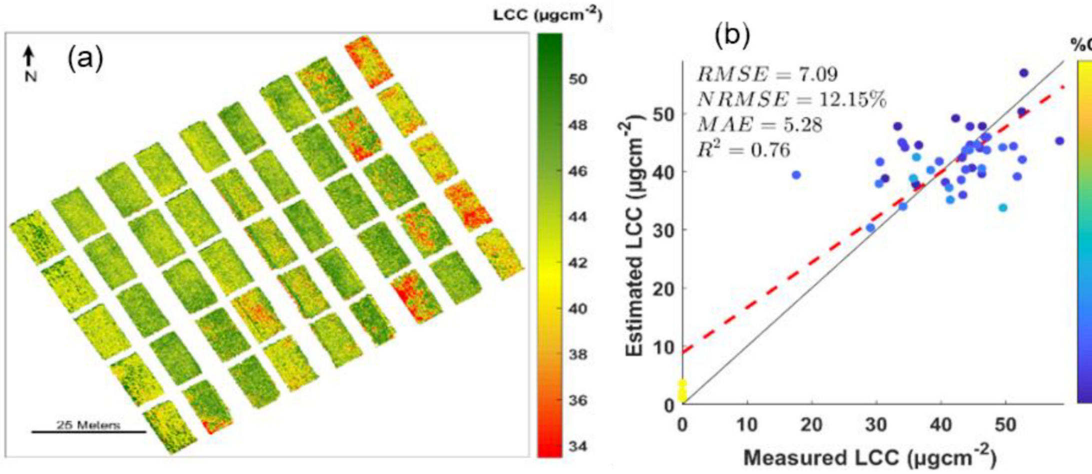

Fig. 4. Chlorophyll content estimated for the Wheat experimental farm using a hybrid approach. (a) Leaf Chlorophyll map, (b) Scatter plot with goodness-of-fit statistics showing the validation of the GPR model against field measurements

using an ASD spectroradiometer in the spectral range of 350-2500nm, of rice plants with different infestation levels of BPH was carried out, to assess the severity (Vidya Madhuri *et al*., 2024; 2025). Substantial variations in the chlorophyll, carotenoid, protein, flavonoid contents and relative water content are observed in infested plants. These alterations serve as vital indicators of pest severity, aiding in cost-effective pest management. Assessing the impact of BPH over 20 and 40 days after infestation (DAI) highlighted significant reductions in chlorophyll, carotenoid, and protein levels. Flavonoid content initially increased after infestation but decreased with high BPH stress after 40 DAI. Relative water content decreased, indicating sustained adverse effects of BPH on rice plants. A distinct change in reflectance pattern between healthy and BPH infested rice plants across all three varieties in green (490–559 nm), yellow (560–584 nm), orange (585–639 nm), and red (640–699 nm) region of visible portion as affected by chlorophyll pigments and in NIR region (700–1800 nm) as affected by cell structure and in water absorption (1915 nm) region of SWIR portion. The specific wavelength band (470, 660,750, 1800, 1915 nm) showing a correlation above 0.8 with pest severity level, was identified as sensitive for assessing BPH damage. Analysis of reflectance changes across wavelengths highlighted that the first derivative has a strong correlation between BPH severity and reflectance in the green region (500–540 nm) and red edge position (680–760 nm). The amplitude of the red edge value decreased with an increase in the severity level of the insects.

Spectral observations in the rice field were taken using a hand-held portable spectroradiometer in the range of 350- 2500 nm, followed by spectral discrimination of the rice blast disease severity levels in rice. Evaluation of 26 existing spectral indices ($r \geq 0.8$) was done corresponding to blast severity levels, and linear regression prediction models were also developed. Further, the proposed ratio blast index (RBI) and normalized difference blast index (NDBI) were developed using all possible combinations of their correlations with severity level, followed by their quantification to identify the best indices. Jeffries–Matusita distance was separating almost all severity levels having values >1.92 except levels 4 and 5. The 26 prediction models were effective at predicting blast severity with R^2 values from 0.48 to 0.85. The best developed spectral indices for rice blast were RBI (R1148, R1301) and NDBI (R1148, R1301). Among multivariate models, SVM was the best model with calibration R^2 =0.99; validation R^2 =0.94, RMSE=0.7, and RPD=4.10 (Mandal *et al*., 2023).

The prediction of rice blast (RB) disease at the asymptomatic stage was conducted using non-imaging hyperspectral data, and it was observed that the IR region was found to be significantly affected by RB disease (Ramalingam, *et al*. 2024). Moreover, the plant protein-specific bands were used for generating novel indices. When validated against measured values, it was observed that the support vector machine shows a strong performance in predicting vegetation health using the indices proposed in this study. The prediction of mango malformation disease occurrence was undertaken by using the spatial interpolation technique (Kriging) of weather parameters, and zonation was done using the threshold values conducive to *Fusarium mangiferae* growth and proliferation (Usha *et al*. 2022). The results revealed that the spatial zonation of areas with mango malformation occurrence is higher for individual weather variables. The model predicted a high probability of mango malformation occurrence in Delhi, Uttar Pradesh and Haryana, followed by Gujarat, Punjab and Jharkhand. In the case of yellow rust disease in wheat crops caused by the Puccinia striiformis f sp. tritici fungus, spectral characterisation results indicate that severely infected plants exhibit higher reflectance in the visible region and lower reflectance in the NIR region. The alteration in reflectance for the infected plant, compared to the healthy plant, is more noticeable in the 530-580 nm region in the visible region; 670-740 nm in the red edge region; and 995 nm to 1195 nm in the NIR range. The red edge position (REP) exhibits the maximum rate of change, referred to as the red edge value (REV), which is closely linked to disease severity levels. On comparing multiple vegetation indices with the chlorophyll content of healthy and YMV-infected soybean crops, it was observed that NDVI was found to be useful in detecting yellow mosaic virus-infected soybean (Das *et al*. 2013).

Input spraying through drones

Artificial Intelligence is revolutionizing agricultural input spraying through drones. In India, where more than 85% of farmers are smallholders. AI-integrated drone spraying enables site-specific management, reduces input wastage and improves crop response. Studies have reported that precision spraying using AI and UAVs can reduce pesticide and fertilizer consumption by 20% while maintaining or improving crop yield by 8-10% compared to conventional blanket spraying. One of the major contributions of AI is variable rate application (VRA). High-resolution drone imagery (2–5 cm spatial resolution) is analysed using machine learning algorithms to detect spatial variability in crop vigour, pest infestation, and nutrient deficiency. Vegetation indices such as NDVI, GNDVI, and SAVI are processed to generate prescription maps. Field experiments in wheat and rice have demonstrated that AI-guided drone spraying can improve nitrogen use efficiency (NUE) by 15–25% and reduce fertilizer losses by 30%. Research trials at ICAR institutes showed that foliar nitrogen application using drones increased grain yield by 7–12% compared to ground-based spraying (Figure 5).

AI also enhances spray deposition and operational efficiency. Drone spraying typically operates at a flight height of 2–4 m, speed of 3–6 m/sec, and spray volume of 10–15 L ha^{-1}, compared to 500 L ha^{-1} used in conventional knapsack spraying. AI algorithms optimize nozzle selection, droplet size (100–300 µm), and flow rate to achieve uniform canopy coverage. Studies indicate that AI-controlled drones improve droplet deposition uniformity by 35–50% and reduce spray drift by 20–30% under moderate wind conditions. Autonomous navigation powered by AI and RTK-GPS provides centimetre-level accuracy (±2.5 cm). Obstacle detection using vision sensors and LiDAR ensures safe operation around trees, electric poles, and field boundaries. Automated mission planning can increase operational efficiency by 40–60%, enabling a single drone to spray 8–12 ha per day, compared to 2–3 ha per day by manual labour.

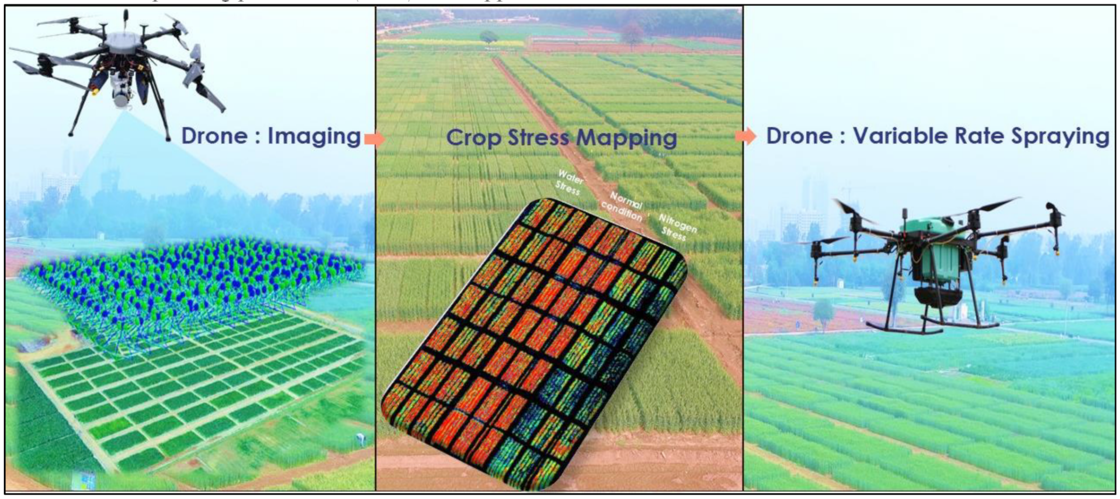

Fig. 5. Drone based variable rate spraying based on varying crop conditions derived from drone imaging

AI-based real-time weather integration further enhances decision-making. Spraying is automatically restricted when wind speed exceeds 3–4 m s^{-1}, temperature crosses 32°C, or relative humidity falls below 40%, ensuring optimal spray retention and absorption. Such smart scheduling has been shown to increase spray effectiveness by 18–22%. Each flight generates geo-referenced data, including application area, spray volume, time, and environmental conditions. This improves compliance with standard operating procedures (SoPs) and supports research validation.

Future of Drones and AI in agriculture

Upscaling the Prediction of Crop Growth Attributes using Space-borne data

The research farms of ICAR-Indian Agricultural Research Institute (IARI) in New Delhi, host various types of crops (grain, pulses, orchids, vegetables, and flowers), and plantations (mango, eucalyptus orange, lemon, and banana, etc.) providing diverse experimental cropland for developing a robust and generic LAI estimation algorithm (Sahoo *et al*. 2024a). In-situ measurements of LAI were collected from these fields using an LAI-2200C Plant Canopy Analyzer during the Rabi season of 2023 on 28th Feb to coincide with Sentinel-2 satellite overpasses, ensuring alignment between ground truth and satellite observations. The simulated spectra generated by the PROSAIL model, in combination with the spectra from the Sentinel-2 image and corresponding LAI values, were used to train the GPR algorithm. The GPR algorithm was tuned and optimized using the Euclidean distance-based active learning method. The tuned GPR model was then used to estimate LAI from Sentinel-2 images, and the estimated LAI at the in-situ locations were compared to their respective observed LAI values. The model estimated LAI from the imagery with an acceptable R^2 value of 0.688. The validated model was then integrated with the GEE and was used to generate the LAI product from the same satellite imagery. The output from GEE was compared to earlier estimated LAI data, and the outputs are a perfect match. Thus, the GEE-integrated PROSAIL-GRP hybrid model can be used to estimate the LAI of the crops at any given day and scale, provided a cloud-free Sentinel-2 is available. Figure 6 shows the flow of the steps involved in developing a hybrid model. This work shows that the upscaling from UAV to Sentinel is plausible and can be extended to their significant crop traits, like CCC and CNC, to improve crop health estimation further.

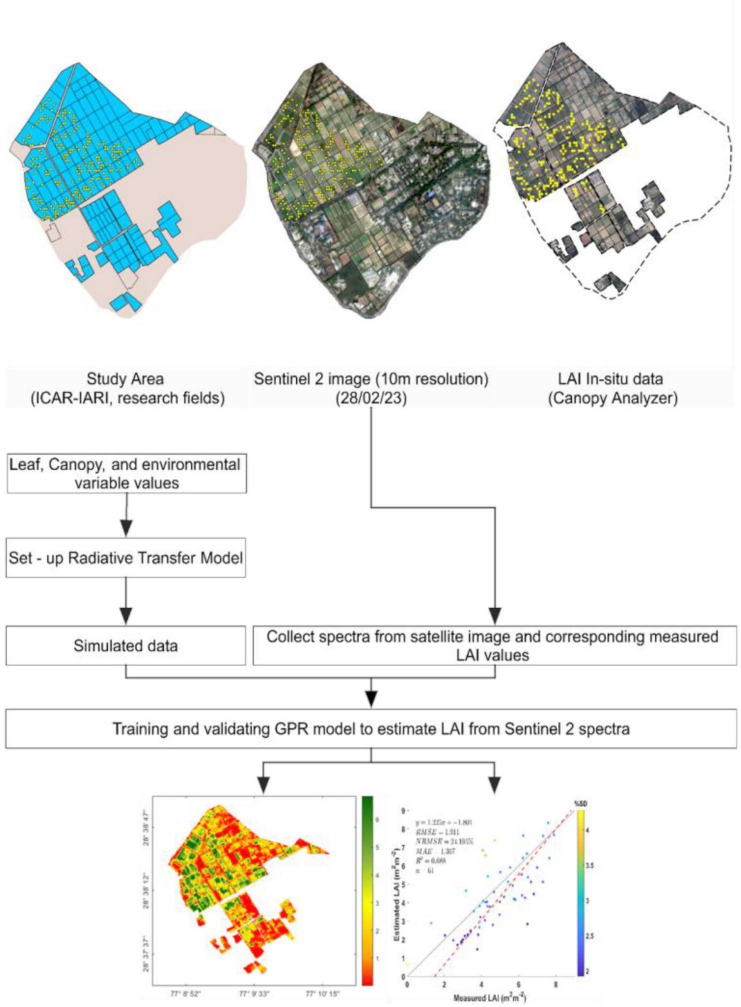

Fig. 6. Satellite based biophysical product (LAI) of the IARI Farm (after Sahoo *et al*. 2024a)

Technological Innovation Pathways

Future innovation pathways emphasise integration, automation, and accessibility. Edge-cloud orchestration will become more tightly integrated, with edge devices performing increasingly sophisticated analytics while maintaining low latency and high bandwidth efficiency. This enables real-time decision-making even in connectivity-constrained environments.

Low-cost and biodegradable sensors address economic and environmental barriers. Research on printed electronics, biodegradable substrates, and energy harvesting aims to reduce sensor costs by an order of magnitude while eliminating disposal burdens. Miniaturisation and multi-parameter sensing improve spatial coverage and information density per sensor. Transfer learning and few-shot learning techniques will reduce AI's data requirements, enabling model deployment in data-scarce contexts. Federated learning allows collaborative model training across farms without sharing raw data, addressing privacy concerns while improving model generalizability.

Autonomous flight-to-prescription pipelines will integrate drone data acquisition, image processing, AI-based analysis, and prescription map generation into seamless workflows, reducing manual intervention and turnaround time. Integration with robotic actuators will close the loop from sensing to action. Digital twins and simulation-based planning will enable farmers to test management scenarios virtually before field implementation, reducing risk and improving decision quality. Integration with genomic data and crop models will support breeding for site-specific adaptation and climate resilience.

Inclusive and Scalable Models

Democratizing precision agriculture requires innovation in business models, not just technology. Shared service models—drone mapping services, equipment rental, sensor-as-a-service—reduce individual capital requirements and enable smallholders to access precision tools. Cooperative ownership and management of precision infrastructure can achieve economies of scale while maintaining farmer control. Open-source platforms for data management, analytics, and decision support reduce software costs and prevent vendor lock-in. Community-driven development ensures tools are adapted to local needs and contexts. Public investment in open-source precision agriculture infrastructure can catalyse inclusive innovation ecosystems. Capacity building through extension services, farmer training programs, and peer learning networks is essential for effective technology adoption. Digital literacy and data interpretation skills are as critical as technical operation skills. Embedding precision agriculture training in agricultural education curricula builds long-term human capital. Inclusive design approaches engage farmers, particularly smallholders and marginalised groups, in technology development to ensure tools meet real needs and constraints. Participatory design, user testing, and iterative refinement improve usability and adoption.

Conclusion

The integration of artificial intelligence with drone technology facilitates data-driven, site-specific, and resource-efficient smart practices for input applications. It supports a truly transformative shift towards green and sustainable technologies aligned with precision farming principles. This made a significant breakthrough in not only improving the crop's yield and plant production, but also made tremendous achievements in soil and water conservation, biodiversity preservation and environmental protection, particularly under the ever-increasing socio-economic needs. Drones have proven to be a powerful technology for achieving rapid, high-resolution data in the form of images across spatial and temporal scales. Their ability to access difficult terrain, fly at low altitudes, provision of frequent observations and real-time data acquisition makes them vital for green technologies in modern agricultural practices. When AI is coupled with drone technology, actionable insights are achieved in the precise management of inputs such as water, fertilizers, and pesticides, thereby enhancing crop production. Moreover, AI-driven models convert voluminous data from IOT sensors, networks, UAV imagery, and field observations to support soil health assessment, estimation of crop growth parameters (LAI, chlorophyll content, nitrogen status, biomass, and yield), variable rate technology (VRT), early detection of pests and diseases, and intelligent decision support systems. In the future, this integration of two powerful technologies provides larger automation, real-time decision-making, compatibility of multiple platforms, and integration with climate-smart, regenerative, and Green farming approaches. Together, not only technologically sound, but also it plays a crucial role in the nation's food security, sustainability, and farmers empowerment.

Acknowledgement

This research activity was conducted under the financial support of the Indian Council of Agricultural Research (ICAR) and is hereby duly acknowledged under the project, titled 'Network Program on Precision Agriculture (NePPA)'.

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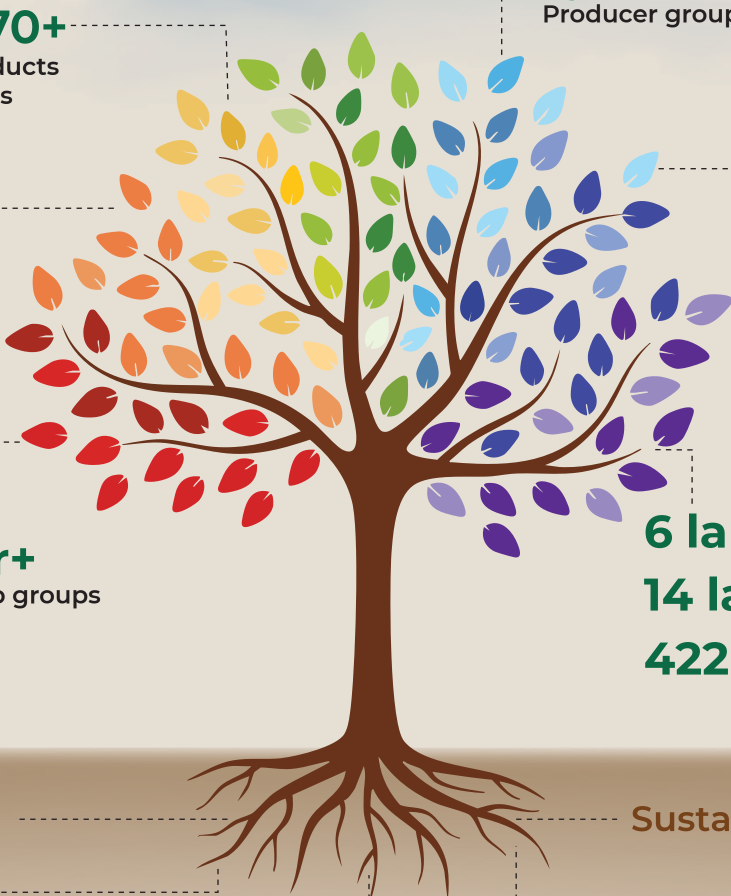
“What We Plant in Values We Harvest in Impact”



Support for **470+** indigenous products 140+ with GI tags

7,500+
Producer groups

1 million+
tonnes of carbon sequestered

60,000+
Fully computerised PACS

1.5 cr+
Self-help groups

6 lakh+ km of roads

14 lakh+ meters of bridges

422 lakh+ hectares irrigated

Inclusion

Sustainability

Grassroots Focus

Cooperative Strength

Trust and Transparency

Celebrating 44th Foundation Day

44TH स्थापना दिवस FOUNDATION DAY

NABARD
THE VOICE OF GRAMEEN BHARAT