Souvenir

National Seminar on Technological Innovations for Transforming Agriculture: The Role of Agrophysics

ICAR-Central Coastal Agricultural Research Institute, Goa
23-24 January 2025

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Jointly Organized by
The Indian Society of Agrophysics
Division of Agricultural Physics
ICAR-IARI, New Delhi
and
Association for Coastal Agricultural Research, Goa

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MESSAGE

I am happy to know that the Indian Society of Agrophysics, New Delhi is organizing the National Seminar on "Technological Innovations for Transforming Agriculture: The Role of Agrophysics" during January 23-24, 2025 at ICAR-CCARI, Goa. It is required to use various technological interventions for utilization of Natural Resources and enhancing agricultural production. The development of new crop varieties helps us to improve the yield potential of crops, however, it is only agrophysics that can assist to unleash the untapped potential. The Agricultural Physicists have played a pivotal role in developing appropriate technologies in different agro-climatic conditions for increasing 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 and AI for precise use of natural resources and also to come out with viable research and management strategies for providing food and nutritional security and employment to the masses.

I wish the Seminar a grand success.

(Himanshu Pathak)

Dated the 17th January, 2025
New Delhi

भारतीय कृषि अनुसंधान परिषद
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डॉ. सुरेश कुमार चौधरी
उप महानिदेशक (प्राकृतिक संसाधन प्रबंधन)
Dr. Suresh Kumar Chaudhari
Deputy Director General (Natural Resources Management)

13.01.2025

Message

I am indeed happy to know that the National Seminar on "Technological Innovations for Transforming Agriculture: The Role of Agrophysics" during 23-24 January 2025 is being organized at ICAR-CCARI, Goa. Globally, impressive achievements have been made in judicious use of natural resources for enhancing agricultural productivity and production. However, the burgeoning demographic pressure coupled with climate change, have posed a formidable challenge to the policy makers, scientists and implementing agencies for providing livelihood to millions of people. The advent of high yielding seeds and subsequent green revolution would not have been that spectacular without matching agrophysical practices under different agro-environments developed over the years by the dedicated Agriculture Scientists. However, the present-day intensive agriculture demands more cautious and pragmatic approaches to ensure environmental safety and sustainable food production. Multi-pronged approaches involving various components of modern-day agriculture need to be evolved to tackle second generation problems of soils, water and environment. I firmly believe that the Indian agriculture has the potential and flexibility to overcome such intimidating tasks with the development and adoption of suitable technologies by devoted agricultural researchers and farmers. In this regard, the theme of the National Seminar "Technological Innovations for Transforming Agriculture: The Role of Agrophysics"' to be held at ICAR-CCARI, Goa is apt and timely. The discussions and deliberations during the Seminar, I hope, would be highly useful and lead to solving the problems associated with agriculture, livelihood and environmental security.

I wish the Seminar a grand success.

(S.K. Chaudhari)

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Message

I am happy that the National Seminar on '"Technological Innovations for Transforming Agriculture: The Role of Agrophysics" to be organized at ICAR-CCARI, Goa during 23-24 January 2025' will have a special focus on the use of agrophysical technologies for smart agriculture and sustainable environment. The development of new crop varieties helps us to improve the yield potential of crops, however, it is only agrophysics that can assist to unleash the untapped potential. We should give simultaneous attention to use of modern technologies for management of natural resources. I hope the Seminar will show the way to formulate the strategies to mitigate the problems for sustainable agriculture towards smart agriculture.

On this occasion, best wishes to the organizers and participants.

Alok Sikka
Country Representative – India & Bangladesh

भा.कृ.अ.प. – भारतीय कृषि अनुसंधान संस्थान, नई दिल्ली–110012 (भारत)
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I am indeed happy to learn that the Indian Society of Agrophysics, Indian Council of Agricultural Research along with the Association for Coastal Agricultural Research, Goa is going to organize a National Seminar on "Technological Innovations for Transforming Agriculture: The Role of Agrophysics"' during 23-24 January 2025 at ICAR-CCARI, Goa. I have been carefully watching the strident Agrophysics research made in the Indian agriculture. The advent of wonder seeds and subsequent green revolution would not have been that spectacular without matching agrophysics research under different agro-environments developed over the years by the dedicated researchers. However, the present-day intensive agriculture demands more cautious and pragmatic approach in order to ensure environmental safety and sustainable food production. In this context, use of agrophysics techniques like drone, remote sensing, simulation modelling, AI, machine learning etc. for developing digital agriculture is indeed an apt subject and relevant in the present context. It is expected that the participants of the Seminar drawn from different spheres of agricultural science will share their expertise and experience towards widening the horizons of knowledge in the proposed area. I congratulate the organizers for choosing a most appropriate theme of the Seminar. I am sure that the discussions and deliberations during the Seminar would be of great benefit to the scientific community in resolving the problems associated with agriculture, livelihood and digital agriculture.

I wish the Seminar a grand success.

(Ch. Srinivasa Rao)

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Rajbir Singh
ADG(AAF& CC)

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Message

It is a pleasure to know that the National Seminar on "**Technological Innovations for Transforming Agriculture: The Role of Agrophysics**" will be held at ICAR-Central Coastal Agriculture Research Institute, Goa, on 23-24 January 2025.

The Green Revolution successfully bridged the gap between the supply and demand for food grains, addressing the needs of the growing population to a significant extent. However, the over use of natural resources, reliance on high external inputs, intensive cropping patterns, and monoculture practices have led to numerous challenges related to food and environmental security. In this context, the application of agrophysics techniques such as drones, remote sensing, simulation modeling, AI, and machine learning for developing smart agriculture is a timely and relevant topic. It is anticipated that participants from various fields of agricultural science will share their expertise and experiences, contributing to the expansion of knowledge in this area.

I am confident that the discussions at the seminar will help in formulating strategies to address the challenges and promote sustainable practices toward smart agriculture.

I wish the seminar great success.

(Rajbir Singh)
Assistant Director General (AAF & CC)

भारतीय कृषि अनुसंधान परिशद
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Dr. A. Velmurugan (डॉ. ए. वेलमुरुगन)
Assistant Director General (SWM)
सहायक महानिदेशक (**एस. डब्ल्यू. एम.**)

New Delhi
15-01-2024

I am happy to know that the National Seminar on "Technological Innovations for Transforming Agriculture: The Role of Agrophysics" is being organized at ICAR-CCARI, Goa during 23-24 January 2025. Impressive achievements have been made world over in judicious use of natural resources management and enhancing agricultural production. However, the burgeoning demographic pressures, have posed a formidable challenge to the policy makers, scientists and all implementing agencies for providing livelihood to teeming millions.

Modern day agriculture faces various challenges due to degradation of natural resources and decline in factor productivity in the face of changing climate. The Agrophysicists have played a pivotal role in developing appropriate technologies for different agro-climatic conditions. There is a need for disseminating these technologies among the farming community in collaboration with extension scientists for wide adaptation and realization of their true potential. I am sure that the seminar will provide a interactive platform for all the stakeholders particularly young scientist. I hope that the delegates attending this Seminar will discuss and interact on issues related to smart agriculture, climate change and management of natural resources to come out with viable research and development strategies for providing sustainable livelihood security, vibrant agricultural economy and sustainable utilization of natural resources.

I wish the Seminar all success in its endeavors.

Yours sincerely

(A.Velmurugan)

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कृषि एवं किसान कल्याण मंत्रालय (कृषि अनुसंधान एवं शिक्षा विभाग), भारत सरकार

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भारतीय कृषि अनुसंधान परिषद

एला, ओल्ड गोवा – ४०३ ४०२ (भारत)

Ministry of Agriculture and Farmers Welfare (Department of Agricultural Research and Education), GOVERNMENT OF INDIA

ICAR-CENTRAL COASTAL AGRICULTURAL RESEARCH INSTITUTE

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डॉ. प्रवीण कुमार / Dr. Parveen Kumar

निदेशक / Director

It gives me immense pleasure to extend my warmest wishes on the occasion of the National Seminar on "Technological Innovations for Transforming Agriculture: The Role of Agrophysics" Jointly Organized by the Indian Society of Agrophysics and Association for Coastal Agricultural Research, Goa at ICAR-Central Coastal Agricultural Research Institute, Goa, during January 23-24, 2025.

The agricultural landscape has experienced significant changes in recent decades as a result of technological improvements. Although issues with food security were addressed by the Green Revolution, the exploitation of natural resources and dependence on intensive farming methods have created serious problems for the sustainability of food, the environment, and resources. This seminar, which focuses on the vital role of agrophysics in utilizing cutting-edge technologies like drones, remote sensing, simulation modeling, artificial intelligence (AI), and machine learning (ML) to create resource-efficient and sustainable agricultural practices, comes at a critical juncture. This seminar offers an excellent platform for researchers, policymakers, extension scientists, and young scientists to come together and engage in meaningful discussions. It is anticipated that these deliberations will lead to actionable strategies for sustainable natural resource management, enhancing productivity, and ensuring food and nutritional security.

I extend my best wishes for the grand success of the National Seminar and hope it paves the way for ground breaking advancements in agricultural science and technology.

20/1/25

(Parveen Kumar)

Indian Society of Agrophysics

Division of Agricultural Physics
ICAR-Indian Agricultural Research Institute
New Delhi 110012, India

DrY S Shivay
President

MESSAGE

It is encouraging to learn that the Indian Society of Agrophysics, in collaboration with the Indian Council of Agricultural Research and the Association for Coastal Agricultural Research, Goa, is organizing a National Seminar on **"Technological Innovations for Transforming Agriculture: The Role of Agrophysics"** from 23–24 January 2025 at ICAR-CCARI, Goa. Significant advancements have been achieved globally in the sustainable management of natural resources and the enhancement of agricultural productivity. However, the escalating pressures of population growth pose substantial challenges to policymakers, scientists, and other stakeholders, including implementing agencies, in ensuring livelihoods for an expanding population.

The agricultural production system is an intricate and multidisciplinary domain that integrates various branches of agricultural sciences. Agrophysicists have made critical contributions by addressing the complexities of the soil-plant-atmosphere continuum and developing context-specific technologies tailored to diverse agro-climatic conditions. It is anticipated that the delegates participating in this Seminar will engage in in-depth discussions on key issues such as smart agriculture, climate change, AI, ML, and resource management. These deliberations are expected to yield actionable insights and innovative strategies aimed at achieving resource-efficient solutions that ensure food and nutritional security, create employment opportunities, and contribute to increasing farmers' income.

I extend my best wishes for the success of the National Seminar and its contributions to advancing agricultural science and practice.

(Y S Shivay)

Contents

Technological Innovations for Transforming Agriculture: The Role of Agrophysics

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ABSTRACT

In today's rapidly evolving world, the agricultural landscape is undergoing a remarkable transformation, thanks to groundbreaking technological innovations. At the heart of this revolution lies agrophysics—a field that combines principles from physics and agriculture to enhance farming practices and improve productivity. Imagine a future where farmers can harness cutting-edge technologies to optimize crop yields, conserve water, and reduce chemical inputs. Agrophysics paves the way for this vision, driving advancements like precision farming, soil health monitoring, and climate-smart agriculture. By leveraging data and innovative tools, farmers can make informed decisions, ensuring sustainable practices while addressing the growing challenges of food security and environmental sustainability. As we explore the potential of agrophysics, we uncover not just a pathway to enhanced agricultural practices, but a holistic approach to nurturing our planet. It is an exciting time for agriculture, with technology poised to make a significant impact—one that promises to feed a growing population while respecting the environment.

Introduction

The challenges of climate change, resource conservation, and feeding a growing global population present significant difficulties for modern agriculture. As a result, interdisciplinary disciplines that blend cutting-edge scientific methods with useful farming practices are becoming increasingly popular among researchers and farmers. Agrophysics is an emerging field that applies concepts and techniques from physics to tackle challenges in agriculture. By focusing on the physical characteristics and processes found in agroecosystems, agrophysics aims to maximize resource use, improve crop quality, and promote sustainability. Comprehending the interactions among soil, water, air, and biological organisms under diverse environmental conditions is essential for contemporary agriculture. While traditional agronomy has made considerable advances in pest control and crop yields, many of these practices still need refinement to address emerging challenges such as water scarcity, soil degradation, and climate change. Agrophysics plays a vital role in this context by enabling more precise monitoring and prediction of key factors that directly influence productivity, such as soil moisture, heat transfer, and the mechanical properties of crops. Additionally, rapid advancements in technology have facilitated progress in automation, data analytics, and sensing. These innovations are grounded in fundamental physics principles, including fluid dynamics in irrigation systems, thermodynamics in greenhouse management, and electromagnetic radiation in remote sensing applications. These solutions are designed and implemented based on agrophysical insights, enhancing the efficiency and environmental sustainability of farm operations. In this context, agrophysics plays a crucial role in connecting fundamental scientific research with practical agricultural applications. Agrophysics assists politicians, agronomists, and farmers in formulating plans based on data that science can verify. By applying physical principles to biological systems, agrophysics makes it possible to study agricultural processes holistically and quantitatively, eventually leading to increased production and sustainability.

Definition of Agrophysics

Agrophysics is a field of study that applies principles, hypotheses, and techniques from physics to examine and solve problems in agriculture. It focuses on the physical properties and processes that govern the interactions between soil, plants, water, air, and agricultural equipment. This includes examining mechanical aspects of activities such as tillage, harvesting, and storage, as well as the exchanges of mass and energy, including heat, water, and nutrient flow. By measuring these phenomena, agrophysics aims to gain a comprehensive understanding of how environmental factors affect crop growth and agricultural productivity (Gliñski *et al.*, 2013).

Agrophysics is founded on the concept that agriculture functions as a complex system, characterized by intricate interactions among its physical, biological, and chemical components. By examining factors such as soil structure, porosity, water retention, and plant biomechanics, agrophysics provides tools to enhance resource utilization, reduce environmental impacts, and strengthen the resilience of agricultural systems.

The significance of Agrophysics in driving technological advancements that reshape agriculture can be highlighted in the subsequent paragraphs:

Innovative Sensors and Smart Farming Tools

Agrophysicists have played a pivotal role in advancing technologies that gather real-time data, facilitating precision agriculture through the application of concepts such as electromagnetic waves, thermodynamics, and fluid mechanics. A significant area of development is soil sensing, where instruments are utilized to measure various parameters, including moisture content, temperature, electrical conductivity, and nutrient levels. Farmers can utilize electromagnetic or capacitance-based sensors to gain real-time insights into soil conditions throughout their fields. This data can be integrated into decision-support systems that provide recommendations for optimal watering schedules and site-specific fertilizer applications. By employing these sensors, farmers can reduce waste, conserve water, and sustain balanced soil fertility by applying resources precisely where and when they are needed. One key advancement in agriculture is the development of smart irrigation systems. These systems use data from soil moisture and weather sensors, along with predictive analytics, to monitor crop water needs. Agrophysics-based irrigation controllers can adjust water delivery in real time, ensuring optimal moisture levels for crops. This approach minimizes water waste and enhances overall crop yields, promoting sustainable agricultural practices. When soil moisture levels fall below a critical threshold, an automated system activates drip irrigation lines or sprinkler systems. This targeted approach to watering not only conserves water—an increasingly scarce resource—but also minimizes the risk of overwatering. By avoiding excessive moisture, the system helps prevent root diseases and reduces nutrient leaching, promoting healthier plant growth and more efficient use of resources. In addition to ground-based sensors, remote sensing technologies—such as drones, satellites, and aerial vehicles—are essential in modern agrophysics research. Equipped with multispectral or thermal cameras, these platforms can collect extensive data on plant health, canopy temperature, and growth patterns. By analyzing spectral signatures, farmers can detect pest or disease outbreaks at an early stage, identify areas within their fields that suffer from nutrient deficiencies, and implement timely intervention measures. The capabilities of this analysis are further enhanced by Internet of Things (IoT) devices, which connect sensors, farm machinery, and data platforms. These IoT ecosystems facilitate a continuous flow of data from the field to the farmer's computer or smartphone, enabling remote monitoring and automated decision-making. Over time, machine learning algorithms can analyze historical data to refine their recommendations, creating a feedback loop that optimizes farm operations. Innovative sensors and smart farming tools, developed through agrophysics research, are revolutionizing agriculture into a data-driven enterprise. By providing precise, real-time insights into complex biophysical processes, these technologies empower farmers to use inputs more judiciously and respond proactively to changing conditions. The outcome is greater efficiency, a reduced environmental impact, and a more sustainable future for global food production (McKenzie and Williams, 2015).

Agriculture finds itself at a crucial juncture where the needs of a burgeoning global population converge with pressing environmental challenges. To respond to the increasing strain on land and water resources, farmers and researchers are leading the way by embracing innovative technologies that facilitate more efficient and sustainable food production. Historically, farming has depended on observational skills and experiential knowledge; however, modern practices now incorporate advanced measurement tools and data analytics to enhance operations. This integration of traditional wisdom with contemporary science is often referred to as "smart" or "precision" agriculture, marking the advent of a data-driven approach to resource conservation and management.

In the era of modern agriculture, four key technological domains have emerged as central to transforming farming practices: sensors for tracking soil moisture and nutrients, real-time monitoring devices connected via the Internet of Things (IoT), remote sensing platforms such as satellites and drones, and comprehensive data analytics underpinned by precision agriculture techniques. Each component addresses a crucial aspect of agricultural management—whether by detailing soil conditions, automating field oversight, diagnosing plant stresses from above, or turning complex datasets into actionable plans. Together, these innovations form a synergistic ecosystem. Soil sensors continuously monitor water and nutrient levels, while wireless networks transmit this data to intelligent systems. Drones and satellites conduct broad-scale assessments of crop health, and advanced analytical tools further refine the outcomes of these processes. The ultimate goal is to create a more adaptive and sustainable farming approach that can respond rapidly to environmental changes and resource challenges. As climate variability increases and populations continue to grow, these innovations are poised to play an even more significant role in global food security. In this text, we will delve into each of these technological pillars, examining how they converge to transform modern agriculture and foster a more resilient future.

Soil Moisture and Nutrient Sensors

Soil serves as the physical and biological foundation essential for agriculture; however, variations in soil conditions often pose challenges to achieving consistent, high-yield production. Traditional methods for assessing soil moisture and nutrient levels—such as digging small pits, conducting basic hand-feel tests, or performing infrequent laboratory analyses—often fall short in capturing localized differences or responding to dynamic changes. This shortcoming can result in the overutilization of resources like irrigation water and chemical fertilizers, leading to increased costs and adverse environmental effects. Nutrient sensors are capable of detecting essential elements such as nitrogen, phosphorus, potassium, and key micronutrients. Utilizing ion-selective electrode technology, these devices provide instant readings of nutrient levels in the root zone. When combined with historical data on previous inputs, yield outcomes, and environmental factors, nutrient sensors enable a "feed as needed" approach. Rather than applying uniform fertilization across an entire field, farmers can deliver additional nutrients precisely where deficiencies are identified. This precision not only helps conserve fertilizers but also protects water systems from nutrient leaching, thereby fostering healthier ecosystems (Kashyap and Kumar, 2021).

Precise Tracking of Soil Moisture

Technologies such as time domain reflectometry (TDR) and capacitance measurement provide a precise method for analyzing soil moisture content. These sensors assess volumetric water content at particular depths and locations by measuring the soil's dielectric properties. The data is typically transmitted via wireless or wired connections, resulting in real-time maps of soil moisture levels that are continuously updated. Instead of following broad irrigation schedules, farmers can now tailor water delivery to the specific needs of different areas, thereby avoiding the adverse effects of under-watering or over-watering. This targeted approach reduces water waste, minimizes energy consumption, and helps address issues like soil salinization and runoff associated with excessive irrigation. When strategically deployed, multiple soil sensors create an interconnected system that provides comprehensive insights into field conditions. Modern sensor arrays can transmit data to cloud-based platforms or mobile applications for continuous monitoring. Alerts and threshold-based triggers can recommend immediate actions, such as adjusting irrigation levels or implementing targeted fertilization. Over several growing seasons, these sensors accumulate extensive datasets that reveal patterns related to water requirements, soil fertility, and productivity outcomes. Machine learning models can use this information to forecast future soil behavior and guide long-term land management strategies. Sensor technology refines day-to-day operations and underpins more informed planning for sustainable resource use (Tornese *et al*., 2024).

Internet of Things (IoT) Devices for Real-Time Monitoring

Although soil sensors provide valuable insights, the Internet of Things (IoT) serves as the communication framework that enables various technologies to work together seamlessly. In the context of agriculture, IoT generally describes a system in which multiple sensing and operational devices transmit data through local or global networks to a centralized hub. IoT-enabled devices encompass a variety of applications, including automated weather stations, greenhouse climate controllers, and sensors integrated into farm machinery. These devices collect and share information on critical factors such as temperature variations, humidity levels, wind speed, and machine performance. All of this data converges into a centralized software platform, enabling growers to monitor their entire operations in real-time, typically through a mobile dashboard. For instance, if an impending heatwave poses a risk of wilting crops, the system can automatically activate supplemental irrigation in the affected areas well before the plants show any visible signs of stress. One of the most significant transformations brought about by IoT is the shift from manual oversight to automated responses. Based on thresholds established by growers or derived from algorithmic predictions, IoT networks can autonomously activate irrigation valves, open greenhouse vents, or even operate heating units without the need for human intervention. Furthermore, when the network detects equipment malfunctions or anomalies in environmental conditions, it can promptly send automated alerts, thereby preventing minor issues from escalating into major problems. This enhances both efficiency and reliability, ensuring that critical tasks remain on schedule and minimizing downtime during peak planting or harvesting seasons. Additionally, IoT systems cultivate a comprehensive repository of operational knowledge by continuously gathering data regarding machinery usage, livestock wellbeing, weather patterns, and soil conditions. Over time, analytical models refine their accuracy by learning from data streams, resulting in increasingly precise forecasts. Whether it's predicting pest outbreaks, optimizing greenhouse microclimates, or recommending maintenance schedules for tractors, these forecasts minimize uncertainty and enhance productivity. As connectivity in rural areas improves and sensor technologies advance, IoT-based monitoring is set to become the foundation of a fully integrated and continuously adaptive farming landscape (Sharma and Shivandu, 2024).

Drone- and Satellite-Based Remote Sensing

In-field devices offer precise local data, while remote sensing technologies expand the farmer's viewpoint. Drones and satellites can capture aerial images and data to assess crop conditions, identify diseases, and provide macro-level insights that ground sensors might overlook. Equipped with cameras capable of capturing multispectral or thermal images, drones can uncover indications of plant health that are invisible to the naked eye. One of the leading metrics for assessing plant health is the Normalized Difference Vegetation Index (NDVI), which utilizes near-infrared and visible light reflectance to evaluate plant vigor. Drones efficiently cover agricultural fields and provide high-resolution imagery, enabling farmers to identify issues such as uneven growth, pest damage, or irrigation inconsistencies at an early stage. Thermal sensors can detect cooler or hotter areas, indicating potential problems like uneven water distribution or the emergence of pathogenic threats. By conducting frequent, targeted flights, farmers can respond proactively, taking measures such as precise pesticide applications to prevent infestations from spreading. Conversely, satellites provide extensive coverage, ranging from localized farmland to entire countries. Platforms such as Sentinel and Landsat provide frequent imagery that allows for effective monitoring of changes throughout the growing season, though their spatial resolution is generally lower than that of drone-based systems. Nevertheless, these satellite images are crucial for large-scale operations and long-term studies, enabling analysts to monitor significant weather events, identify drought conditions, and observe evolving land use patterns. Numerous satellite data sources are readily accessible at no cost, providing smallholder farmers and researchers the opportunity to obtain regional imagery, even when they may not have the means to conduct drone flights. An essential aspect of remote sensing is the validation of data through on-ground measurements, often referred to as "ground truthing." Utilizing data from soil sensors or leaf samples helps to verify and enhance the accuracy of aerial or satellite observations. Drones and satellites are capable of detecting anomalies, but farmers often require in-field assessments to pinpoint specific issues such as nutrient deficiencies, diseases, or pest infestations. By integrating remote sensing data with IoT networks, an automated workflow can be established. For example, if drone imagery indicates potential stress in a particular area of a field, the system can instruct ground robots or farm personnel to investigate and address the problem. This cohesive, multi-faceted approach streamlines the entire process, transforming high-level aerial data into targeted, actionable solutions on the ground (Sahoo, 2022).

Precision Agriculture and Data Analytics

Gathering extensive data from sensors, IoT devices, or remote sensing platforms is truly valuable only when it drives decisions that enhance farming outcomes. This is where precision agriculture and its associated analytical techniques come into play. Instead of applying a uniform approach across an entire field, precision agriculture takes into account the varying conditions within that field, ensuring each section receives tailored care. This approach frequently incorporates geographic information systems (GIS) and variable-rate technology (VRT). Farmers categorize their fields into management zones by analyzing factors such as soil types, field elevation, historical yields, and other relevant parameters. Utilizing Variable Rate Technology (VRT), equipment can apply fertilizers, seeds, or pesticides in quantities that align with these localized conditions. High-fertility areas may need minimal interventions, while depleted zones can benefit from additional inputs. Furthermore, irrigation schedules can be calibrated to meet the specific water requirements of each sub-zone. This zoned strategy conserves resources and mitigates environmental harm caused by runoff, leaching, or unnecessary energy consumption. Advanced machine learning algorithms and big data solutions enable farmers to analyze real-time sensor data in the context of historical trends. By identifying recurring patterns—such as the correlation between certain weather conditions and pest outbreaks—predictive models can inform farmers of potential challenges. This foresight facilitates timely interventions, protects yields, and helps prevent costly damages. Over multiple seasons, the models become more refined, capturing nuances such as the interplay between soil composition, crop variety, and precipitation rates. Eventually, they might suggest adaptive strategies like shifting planting times or rotating crops to mitigate likely yield shortfalls. By employing a data-driven approach, precision agriculture also fosters resilience in the face of climate volatility. If changing weather patterns cause extended dry spells or heavier-than-usual rainfall, real-time monitoring systems will capture the shifts, and analytics will integrate them into future planning. This feedback loop enables continual learning. Farmers can revise their irrigation infrastructure, refine fertilizer mixes, or experiment with drought-resistant crop varieties, all based on the comprehensive evidence gathered and analyzed. In a broader sense, precision agriculture's incremental improvements build an adaptable, ecologically conscious form of food production (Akhter and Sofi, 2022).

These innovations mutually reinforce one another. Soil sensors provide detailed, localized insights regarding water and nutrient levels. IoT frameworks aggregate this data into actionable dashboards, enabling timely responses and maintenance alerts. In parallel, drones and satellites deliver a comprehensive aerial—or even orbital—perspective, revealing broader trends and regional patterns. Ultimately, principles of precision agriculture paired with analytical tools integrate all these inputs, assisting growers in developing a field-specific strategy for delivering the optimal amounts of water, fertilizer, and protective treatments to each area. It is important to recognize that this transformation presents certain challenges. Dependable network infrastructure, initial equipment expenditures, and the need for user training are all obstacles to overcome. Nevertheless, improvements in connectivity, declining sensor prices, and the rise of intuitive analytics platforms are making these technologies increasingly available to a wider range of producers. Once primarily utilized by large-scale commercial enterprises, data-driven farming is now gradually extending to smaller operations, thereby contributing to broader sustainability and productivity objectives.

GIS and GPS applications for site-specific crop management

GIS and GPS applications have become essential tools for site-specific crop management by highlighting the spatial variability within fields. Prior to the widespread adoption of these technologies, farmers commonly assumed that their land was uniform, applying seed, water, and fertilizer at the same rate across all acres. However, as time progressed, many producers recognized that this uniform method often resulted in wasted inputs and inconsistent crop growth. By integrating GPS receivers with GIS software, growers can produce detailed digital maps of their fields, showcasing variations in soil properties, topography, and yield history. These maps facilitate the creation of site-specific management zones, allowing for tailored treatments based on the unique needs of each area. For instance, a sandy section that is prone to water runoff may require more frequent, shorter irrigation intervals. In contrast, a clay-rich region with superior water retention can be managed with fewer but deeper watering sessions. The same principle applies to fertilization: high-fertility zones may necessitate minimal amendments, while less productive soils require higher nutrient levels to promote robust plant growth. GPS-based systems in tractors and applicators enable seamless adjustments to application rates as machinery transitions between different zones, delivering a customized response that corresponds with the unique microenvironments within the field. In addition to optimizing inputs, GIS and GPS technologies assist farmers in monitoring field boundaries, planning crop rotations, and maintaining precise records for regulatory compliance and certifications. Over time, these historical data points create a comprehensive knowledge repository regarding the performance of each field under various agronomic strategies and weather conditions. By analyzing this information, farmers can uncover long-term improvements—such as enhanced drainage, erosion control, and organic matter replenishment—that bolster the resilience of their fields. Moreover, as equipment manufacturers increasingly integrate GNSS (Global Navigation Satellite System) compatibility and automated guidance into their machinery, site-specific interventions can be executed with minimal manual adjustments. This advancement allows operators to concentrate on broader management decisions rather than the tedious task of steering (Singh *et al*., 2022).

Big data, AI, and machine learning in yield prediction and Cloud-based decision-support systems

As geospatial tools gained traction, the volume and complexity of data generated by farms began to surpass the interpretive capabilities of human operators. This is where big data analytics, AI, and machine learning come into play, enhancing both the precision of yield prediction and the efficiency of resource planning. Scientists gather extensive datasets that range from historical weather patterns to real-time readings from soil moisture sensors, often covering thousands of acres across multiple growing seasons. Machine learning algorithms excel at sifting through these layers of information, finding relationships that may not be obvious to human observers. For instance, a specific sequence of rainfall events, soil temperature patterns, and fertilizer timings might consistently correlate with bumper yields for a specific crop variety. By detecting such patterns, the algorithms can forecast the best windows for planting or identify early signals of pest infestations. The application of AI does not stop at yield forecasting. Machine learning models play a crucial role in diagnosing plant stress by analyzing spectral data from satellite or drone imagery, enabling the distinction between diseased and healthy crops. In certain instances, real-time or near-real-time anomaly detection can alert farm staff to investigate and address issues before they escalate. While no predictive model is perfect, the ability to make data-driven decisions at scale enhances resource efficiency, ultimately lowering the costs and environmental impact of agricultural operations. Furthermore, as farms accumulate more data over the seasons, these algorithms improve their predictive accuracy. Over the years, the relationship between weather variables, input levels, and crop yields has become increasingly well understood, enabling farmers to plan more precisely. While big data and AI algorithms provide high-level forecasts and diagnostics, the challenge often resides in translating this complex information into practical guidance for on-farm operations. Cloud-based decision-support systems bridge this gap by presenting analytical outputs in user-friendly dashboards and automated alerts. Historically, farm owners and managers often relied on separate spreadsheets, software applications, or physical notebooks to monitor various aspects of their operations, from planting schedules to irrigation intervals. This fragmentation could hinder timely decision-making. However, cloud-based platforms consolidate these diverse data streams into a single interface, allowing access from a computer in the farm office or a smartphone in the field. With real-time updates on weather forecasts, sensor readings, and aerial imagery, these platforms can generate context-specific recommendations, such as adjusting water delivery for a particular field or applying fungicides in response to anticipated disease pressure (Toromade and Chiekezie, 2024).

Furthermore, the cloud's computing capabilities allow farms with limited local infrastructure to utilize advanced analytical models. Rather than investing in expensive servers or specialized software on-site, users can connect to a remote service that manages the intensive computational tasks. This approach democratizes precision agriculture technologies, making them accessible not only to large agribusinesses but also to smaller and mid-sized operations. Machine learning models hosted in the cloud continuously enhance their capabilities by aggregating data from a multitude of clients, facilitating regional and global knowledge-sharing. Over time, these collaborative networks can generate new best practices tailored for various climates and crops. The adaptability of cloud-based solutions ensures that if a farmer chooses to expand their acreage or diversify into a new crop, the system can easily incorporate additional data and provide updated recommendations without necessitating a substantial hardware overhaul. At the core of these innovative technologies lies the fundamental objective of enhancing soil health and boosting crop productivity. Regardless of the advancement of digital analytics, the fundamental physical and biological processes in the soil largely dictate a farm's long-term sustainability. A technology-driven approach must not overlook the essential principles of maintaining a balanced soil ecosystem that fosters robust root development and efficient nutrient absorption. Reducing soil compaction, enhancing organic matter, and preserving beneficial microorganisms are critical factors for crop health. Sensors and data analytics can effectively inform decisions about when to apply compost or cover crops and how frequently to rotate fields. If yield data from specific zones consistently falls short, a thorough investigation can reveal underlying soil structure problems or low organic matter levels, prompting targeted interventions such as the planting of nitrogen-fixing cover crops (Paul *et al.*, 2022).

Precision soil amendments guarantee that each area receives exactly what it requires, reducing waste and the potential for pollution. Erosion risks can be identified using GIS technology, leading to the implementation of measures such as terracing or buffer strips in regions susceptible to runoff. Additionally, variable-rate lime applications can address pH imbalances, fostering a more conducive environment for microbial activity. Over multiple seasons, healthier soils yield more stable production and necessitate fewer chemical inputs, creating a virtuous cycle where ecological health and agricultural productivity enhance one another. The collaboration of GIS and GPS technologies, big data analytics, cloud-based platforms, and a commitment to soil health illustrates the significant advancements in agriculture toward an integrated approach. Farmers are no longer faced with the dilemma of choosing between productivity and environmental stewardship; they can now utilize hyper-local insights and advanced computational tools to refine their decisions—whether it's selecting the optimal seed variety based on historical weather data or determining the appropriate amount of nitrogen to apply in a specific zone. As these methods and tools become more affordable and accessible, their benefits are expected to extend to a wider range of agricultural enterprises globally (Rastogi *et al.*, 2023).

Ultimately, the integration of site-specific crop management, AI-driven yield predictions, digital decision-support systems, and soil stewardship signifies a transforming agricultural paradigm characterized by precision, sustainability, and adaptability. Although uncertainties will always exist—particularly those linked to extreme weather events or emerging pests—this combination of technologies empowers farmers to react more swiftly and effectively than ever before. Producers who adopt these methods not only improve their current profitability but also establish a foundation for lasting agricultural resilience, equipping themselves and future generations to address the challenges of feeding a growing global population within the constraints of an evolving environment.

Advancing soil physics research involves exploring various aspects of soil behavior, properties, and processes that influence agricultural productivity, environmental sustainability, and land management. Key areas of focus include: soil structure and compaction; soil water dynamics; soil nutrient cycling; soil-plant interactions, soil erosion and conservation; and impact of climate change. Utilizing remote sensing, soil moisture sensors, and GIS tools to collect and analyze data for better soil management practices. By focusing on these areas, researchers can contribute to better agricultural practices, soil conservation, and environmental protection. Collaborative efforts among scientists, policymakers, and land managers are essential for translating research findings into effective soil management strategies.

Conclusion

Modern developments grounded in agrophysics have ushered in a new era of sustainable agriculture by offering precise methods to measure, interpret, and govern the intricate relationships linking soil, water, plants, and climatic factors. By applying physics-based insights to farming systems, scientists and practitioners can better understand soil structure, water movement, nutrient pathways, and energy balances—knowledge that directly informs more efficient, eco-conscious approaches to crop cultivation. These breakthroughs are visible at all levels of agriculture, from real-time sensors that continuously track soil properties at various depths to drones and satellites that detect variations across fields and automated decision-support mechanisms that convert raw data into practical management actions. Integrating physical science with digital tools—such as machine learning, big data analytics, and cloud-based infrastructures—amplifies this potential, enabling in-depth analysis and highly targeted interventions across various farms. As a result, agrophysics empowers producers to refine irrigation practices, fertilizer usage, and pest management, maximizing yield and minimizing waste and environmental strain. Ultimately, agrophysics embodies a crucial link between rigorous scientific research and hands-on agriculture. In a world where global food demand continues to climb alongside mounting environmental constraints, this interdisciplinary domain will be integral to advancing a resilient, productive, and responsible farming sector.

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The Role of Soil Health Card in Transforming Indian Agriculture

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ABSTRACT

The Soil Health Card (SHC) scheme, launched in 2015 by the Government of India, is a transformative initiative designed to enhance agricultural productivity and sustainability. This scheme provides farmers with specific recommendations for balanced nutrient management tailored to their soil conditions. It addresses critical challenges such as soil fertility issues, nutrient imbalances, and the excessive use of chemical fertilizers. The SHC scheme covers over 120 million farmers and spans 141 million hectares through standardized soil sampling and testing. It incorporates data on 12 key soil parameters and offers guidelines for nutrient application for six major crops. As a result, the initiative has significantly reduced fertilizer misuse, improved crop yields, encouraged the adoption of organic farming practices, and increased farmers' net income by 30 to 40%. Despite these accomplishments, some challenges remain, including infrastructure gaps, low awareness among farmers, and delays in implementation. To enhance the scheme's efficiency, innovative solutions are proposed, such as integrating digital technologies, introducing soil health indices, and fostering public-private partnerships. By promoting site-specific nutrient management and raising awareness about soil health, the SHC scheme is well-positioned to play a crucial role in achieving sustainable agriculture and ensuring food security in India.

Introduction

"*Food is only as healthy as the soil in which it is grown.*"

-Anne Gibson

Agricultural productivity and long-term sustainability are fundamentally linked to healthy soil. Soil health can be defined as "the capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Safley, 1997). The first step toward sustainable agricultural production is adopting scientifically proven cropping patterns and fertilization methods. In India, agriculture plays a crucial role, supporting nearly 58% of the population and contributing around 18% to the GDP (Chand, 2020). Therefore, maintaining soil health is essential for ensuring the nation's food security, strengthening the rural economy, and promoting environmental sustainability. Total food grain production in India increased from 170 million tonnes (Mt) in 1990 to 252 Mt in 2016, but this growth has come with challenges, including imbalanced fertilizer use, excessive reliance on chemical inputs, intensive agricultural practices, and the use of chemical plant protectants. India's fertilizer consumption has risen significantly, from 0.07 Mt in 1951–52 to 25.95 Mt in 2016–17, with per hectare usage increasing from less than 1 kg to 130.8 kg. However, the consumption ratio of nitrogen, phosphorus, and potassium (NPK) in 2015 was 6.7:2.4:1, heavily favoring nitrogen, compared to the ideal ratio of 4:2:1 recommended by the Fertilizer Association of India. As the second-largest global consumer of fertilizers after China, India accounted for 15.3% of the world's nitrogen, 19% of phosphorus, and 14.4% of potassium consumption in 2017 (Agriculture Statistics at a Glance, 2017). This imbalance highlights the urgent need for a more balanced and judicious use of fertilizers, specifically through site-specific nutrient management, to improve soil health and ensure agricultural sustainability.

Govt. initiatives so far

The ongoing disproportionate use of nitrogen (N) and phosphorus (P) fertilizers has exacerbated the nutrient demand-supply gap, leading to reduced nutrient use efficiency and diminished economic returns. To tackle these issues, the government has introduced initiatives in recent five-year plans aimed at strengthening soil testing laboratories (STLs) and promoting balanced, integrated fertilizer application. The soil testing program in India began in the year 1955-56 with the establishment of 16 STLs under the Indo-US Operational Agreement for the "Determination of Soil Fertility and Fertilizer Use" initiative. The program gained significant traction during the 11th Five-Year Plan (2007–2012) through the National Project on Management of Soil Health and Fertility, which allocated ¹ 429.85 crores for the establishment of new soil testing laboratories and the enhancement of existing facilities to include micronutrient testing capabilities (Fishman *et al.*, 2016). This initiative was further expanded during the 12th Five-Year Plan (2012–2017).

Launch of Soil Health Card (SHC) scheme

The Soil Health Card (SHC) scheme was launched by honourable Prime Minister shree Narendra Modi on February 19, 2015, in Suratgarh, Rajasthan. This initiative is a part of the Government of India, implemented under the Ministry of Agriculture and Farmers' Welfare through the Department

Figure 1. Soil Health Card

of Agriculture in all states and Union Territories. The Soil Health Card serves as a physical or digital document that details the status of 12 essential soil parameters, including pH, EC, Organic Carbon, and the availability of Nitrogen (N), Phosphorus (P), Potassium (K), Sulphur (S), Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu), and Boron (B). It also includes the farmer's personal information and plot details (MoA&FW, 2016). Based on this thorough soil analysis, the SHC provides recommendations for manure, fertilizers, and amendments suited for at least six crops—three kharif crops and three rabi crops—to enhance nutrient management. The initiative aims to issue an SHC to each of the 140 million farmers in the country every three years on an ongoing basis. As of the 2019-20 period, approximately 22.91 crore soil health cards had been generated and issued to farmers under Cycle 1 (2015-17), Cycle II (2017-19), and the model village program (2019-20) (soilhealth.dac.gov.in).

Objectives of the scheme

The scheme has the following objectives:

Issue Soil Health Cards (SHCs) to all farmers every three years, providing a foundation for addressing nutrient deficiencies in fertilization practices.

- Identify soil fertility constraints using standardized sampling and analysis methods and formulate Taluka/Block-level fertilizer recommendations.
- Promote soil test-based nutrient management to improve nutrient use efficiency.
- Build the capacities of district- and state-level staff and progressive farmers to encourage balanced nutrient management practices.
- Enhance the efficiency of soil testing laboratories (STLs) through capacity building, involvement of agricultural and science students, and strengthening links with ICAR and State Agricultural Universities (SAUs).
- Improve soil quality and profitability to farmers.
- To generate employment for the rural youth.

Methodology and implementation

Under the Soil Health Card (SHC) scheme, the cropped area is categorized into 10-hectare grids for rainfed lands and 2.5-hectare grids for irrigated lands. This distinction reflects the greater nutrient variability found in irrigated soils, which can be affected by runoff and leaching. Given that the average size of Indian farms is 1.05 hectares, each grid in rainfed regions typically encompasses 9 to 10 farmers, while in irrigated areas, it usually covers 2 to 3 farmers. Soil samples are collected by combining 5 to 6 subsamples from each grid, with the results shared among the farmers in that particular grid. Over a span of two years, approximately 34.3 million grid samples were collected across India, covering 141 million hectares of net cropped area and benefiting about 120 million farmers. This results in an average of 46,414 grid samples per district, or 52 samples per village, making it an efficient strategy to meet the needs of smallholder farmers (Reddy, 2019). The pooled sampling method facilitated thorough soil health assessments, ensuring that farmers had widespread access to scientific nutrient recommendations.

In India's federal system, agriculture is primarily under state jurisdiction, with the implementation of programs managed by state governments. However, some initiatives, such as the

Soil Health Card (SHC) scheme, receive central funding and sponsorship (Muralidharan *et al*., 2016). Consequently, the success of the SHC scheme at the local level is heavily dependent on state capabilities, including the availability of skilled personnel and the number of soil testing laboratories per 1,000 hectares. Variations in these resources across states significantly influence the scheme's effectiveness and reach. For instance, Kerala leads in soil sample collection, with 969 samples per 1,000 hectares, followed by Tamil Nadu, Gujarat, Uttar Pradesh, and Bihar, which have between 247 and 544 samples. Moderate collections (157–246 samples) were reported in states such as Jammu & Kashmir, Haryana, Telangana, and Andhra Pradesh, while regions like Odisha and Assam collected between 27 and 156 samples. Manipur and Delhi recorded the lowest numbers, with fewer than 26 samples per 1,000 hectares (Reddy, 2019). An impact study conducted by Reddy in 2019 concluded that after the first cycle (September 2017), the SHC scheme achieved significant progress, meeting 100% of the target for sample collection, 93% for soil testing, and 80% for SHC printing, with 97% of the cards distributed to farmers. However, the progress was highly uneven. Some states, including Karnataka, Tamil Nadu, Chhattisgarh, Uttar Pradesh, Maharashtra, Telangana, and Andhra Pradesh, performed better than others. The second phase (2017-2019) focused on retesting soil samples and updating the SHCs for farmers who were covered in the first phase, while also expanding coverage to new farmers and farm holdings. Subsequent phases continued to follow a similar approach, aiming to provide updated SHCs to all farmers every two years. As of February 2020, a total of 429 new static soil testing laboratories (STLs), 102 new mobile STLs, and 8,752 mini STLs had been established.

Role in Indian agriculture

Nutrient consumption pattern

The study conducted by Singh *et al*. (2023) demostrated that the adoption of Sustainable Agriculture Practices (SHCs) by farmers in Bareilly District, Western Uttar Pradesh, resulted in a significant increase in the use of Farm Yard Manure (FYM) from 14% to 23%. Additionally, the number of farmers using Muriate of Potash (MOP) and Sulphur surged by 25% and an impressive 600%, respectively, for wheat crops. There was also a remarkable rise in FYM application for sugarcane, increasing from 1662.5 ± 378.9 kg/acre to 6623.5 ± 971.9 kg/acre, marking a 298.4% increase. Conversely, the usage of Diammonium Phosphate (DAP) declined by 20.7%, falling from 75 ± 7.3 kg/acre to 59.5 ± 6 kg/acre. In a similar impact study of SHCs, Reddy *et al*. (2017) found that paddy farmers reduced their urea usage by approximately 13%, DAP/SSP by about 12%, and Potassium by around 4%. After the introduction of the SHC scheme, the use of NPK fertilizers consistently decreased. Notably, fertilizer use dropped by 19% in pigeon pea crops. For wheat, the reductions included a 10% decrease in urea, an 18% decrease in phosphorus, and an 11% decrease in potassium application. Furthermore, Gupta *et al*. (2020) reported from Andhra Pradesh that increased awareness of SHCs, along with the provision of free micronutrients for deficient soils, led to a rise in the usage of these micronutrients among farmers. These findings highlight the positive impact of the SHC scheme on nutrient management across various crops by encouraging greater use of organic inputs like FYM and targeted micronutrients, while simultaneously decreasing excessive reliance on chemical fertilizers.

Crop productivity

In Karnataka, Abhishek *et al*. (2020) found that users of soil health cards (SHC) achieved a higher average paddy yield of 75.34 qtl/ha, compared to 71.05 qtl/ha for non-users, with a significance level of 5 percent. This is consistent with the 3.2 kg/ha productivity increase reported in Andhra Pradesh by Ankhila *et al*. (2023). Similarly, research by Jotin Bordoloi and Anup Kumar Das (2017) in Assam, and Singh *et al*. (2017) in Punjab, indicated that soil-tested farmers obtained marginally higher yields across various crops such as maize and basmati rice. In Uttar Pradesh, Singh *et al*. (2023) reported a remarkable 30.8% increase in wheat yields, rising from 14.6 ± 0.4 q/acre to 19.1 ± 0.4 q/acre, alongside a 32.9% increase in sugarcane yields, which grew from 243.9 ± 4.9 q/acre to 324.1 ± 8.1 q/acre. These findings are corroborated by Makadia *et al*. (2017) in Gujarat, who attributed the yield improvements to a balanced supply of organic and inorganic nutrients. Therefore, the adoption of SHC-based fertilizer recommendations across various crops and regions in India has consistently resulted in significant enhancements in crop yields.

Crop diversification

The SHC offers customized recommendations for specific crops based on soil characteristics. This method fosters crop diversification and promotes optimized crop rotations or intercropping systems. Such diversification enhances soil health by mitigating pest and disease outbreaks, improving nutrient cycling, and reducing soil erosion (Lal, 2015). Additionally, it bolsters resilience against climate variability and market fluctuations, resulting in more stable and varied incomes for farmers.

Organic farming practices

The SHC initiative has effectively encouraged farmers to adopt organic farming practices. This shift includes the use of organic manure, compost, biofertilizers, and the incorporation of crop residues and green manures into their agricultural systems (Chander *et al*., 2018). Such practices significantly increase soil organic carbon, improve soil structure and fertility, and enhance the soil's capacity to retain water and nutrients. By embracing organic farming methods, farmers can bolster the overall sustainability of agriculture while also mitigating the adverse effects of climate change on their farming practices.

Economic benefits

The adoption rate of recommended technologies is largely influenced by the economic benefits they provide to farmers. According to Singh *et al*. (2017), the costs of wheat production decreased by ₹ 2,130 per acre, while paddy and sugarcane saw reductions of ₹ 2,164 and ₹ 3,122 per acre, respectively, following the adoption of SHC-based fertilizer recommendations. In Madhya Pradesh, Chouhan *et al*. (2017) reported that net income for paddy farmers increased by 54.79%, rising from ₹ 11,231 to ₹ 17,385 per acre. Soybean farmers experienced a 67.7% increase in net income, while maize farmers saw the most substantial gain of 139%, with net income climbing from ₹ 3,379 to ₹ 8,105 per acre after implementing SHC-based nutrient management. The study conducted by Abhishek *et al*. (2020) found that the total variable cost for SHC users was ₹ 67,616 per hectare, which was lower than the ₹ 70,595 per hectare for non-users. This indicates that adopting SHC-based recommendations not only helped reduce production costs for farmers but also allowed them to achieve higher yields compared to those who did not utilize SHC methods, likely due to the optimized use of resources such as chemical fertilizers and amendments.

Improvement in soil health awareness

The Soil Health Card (SHC) scheme has significantly transformed soil health awareness among farmers and agricultural stakeholders in India. By providing soil-specific information through targeted awareness campaigns, the scheme has empowered farmers to better comprehend the nutrient status of their soil and its direct effects on fertility and productivity (Chander *et al.*, 2018). This increased awareness has led to the adoption of sustainable practices, such as integrated nutrient management (INM) and soil-specific fertilizer application. Supporting this, Niranjan *et al*. (2018) found that SHC holders exhibited a notably greater understanding of INM practices, the implications of imbalanced fertilizer use, and government programs under the Soil Health Mission compared to non-holders. This highlights the SHC scheme's critical role in fostering informed decision-making for enhanced soil management.

Challenges in mass-implementation

Shortage of skilled manpower

The timely collection, testing, printing, and distribution of Soil Health Cards (SHCs) are vital for the success of the scheme. However, these processes heavily depend on the skill levels of soil sample collectors, lab technicians, and the infrastructure of soil testing laboratories. Many states, especially in the northern and eastern regions, experience significant deficiencies in both infrastructure and human resources. For example, Reddy (2019) noted that, on average, each block agricultural officer is tasked with managing 17,000 farmers, highlighting the substantial workload and the urgent need for skilled personnel to effectively support the scheme.

Lack of understanding of SHC

Approximately 48% of farmers successfully adhered to the recommendations provided by the SHC (Reddy, 2019). The primary factors contributing to the low level of understanding and trust in these recommendations were inadequate communication strategies and discrepancies between traditional practices and those recommended by the SHCs. Additionally, the issue is compounded by high illiteracy rates among farmers.

Need for Advanced Tools in Soil Sampling

In many states, agricultural officers still rely on manual techniques to identify farmers' plots for soil sampling. In contrast, states like Punjab and Tamil Nadu have adopted GPS-enabled tablets equipped with integrated village soil maps and predefined grids, leading to substantial improvements in the accuracy and efficiency of soil sample collection. To ensure widespread adoption of these advanced tools across all states, increased budgetary support is essential.

Constraints faced by the beneficiaries

Farmers adopting the Soil Health Card (SHC) scheme encountered numerous challenges (Ghate *et al.*, 2020), with the unavailability of micronutrients identified as the most significant, affecting 66% of participants. Other notable issues included delays in receiving SHCs (68%) and difficulties in calculating fertilizer doses (66%). Additional obstacles were reported, such as trouble sending soil samples to laboratories (38%) and limited internet skills (54%). In Assam, the average distance from farmers' fields to Soil Testing Laboratories was approximately 25.35 km, as noted by Bordoloi and Das (2017). Similarly, studies by Kaur *et al*. (2020) and Patel *et al*. (2022) emphasized barriers like outdated laboratory equipment and inadequate extension services. Furthermore, Niranjan *et al*. (2018) pointed out financial constraints in purchasing fertilizers (34%) and doubts regarding the reliability of SHC recommendations (47%) as significant factors hindering effective adoption.

Future scope and recommendation

Model demonstration

To build farmers' confidence in the recommendations based on the Sustainable Agriculture and Climate (SHC) approach, establishing model farms in each village can be an effective strategy (Reddy, 2019). These farms would showcase the tangible benefits of adopting SHC-based practices, fostering trust in the scheme. Additionally, the results of these demonstrations should be widely shared through wall posters, display boards in community centres, and local mass media campaigns. Creating advertisements and slogans in regional languages can further enhance awareness and encourage the broader adoption of SHC recommendations.

Introducing Soil Health Index for Better Adoption

Incorporating a Soil Health Index on the Soil Health Card (SHC) can serve as a valuable indicator of the overall health of the soil for farmers. This index could categorize soils into grades such as A, B, and C, with updates provided at each SHC cycle based on soil test results. Such a grading system would encourage farmers to make improvements in soil health, for example, striving to elevate their rating from grade C to grade A. Enhanced soil health may also lead to advantages such as increased land rents and market values. Furthermore, the government could offer incentives or subsidies to farmers who successfully improve their Soil Health Index, thereby fostering sustainable soil management practices.

Leveraging Digital Technologies

Integrating digital technologies such as remote sensing, digital soil mapping, and mobile applications can significantly enhance the accuracy and accessibility of soil health information. Crop performance can be assessed on a large scale using remotely sensed NDVI (Normalized Difference Vegetation Index) data. Recent studies (Mulla, 2013; Barman *et al*., 2013) have demonstrated that near-infrared (NIR) and visible-near-infrared (VNIR) spectroscopy are effective in estimating essential soil health indicators. These indicators include soil texture, organic and inorganic carbon, total nitrogen, cation exchange capacity (CEC), pH, potential pollutant metals (e.g., As, Cd, Pb), enzyme activities, and carbon and nitrogen mineralization, among others. These advanced tools not only facilitate efficient data management and monitoring but also provide farmers with more specific and tailored recommendations (Rossiter, 2017).

Farmers' suggestions

Singh *et al*. (2023) highlighted several recommendations from farmers aimed at enhancing the effectiveness of the Soil Health Card (SHC) scheme. All farmers (100%) underscored the necessity for the government to assume full responsibility for soil testing. Moreover, 77.5% advocated for the organization of additional training programs focused on scientific soil sampling methods and the significance of micronutrients and biofertilizers in sustaining soil fertility. The need for follow-ups by extension experts was emphasized by 92.5% of farmers to monitor the progress of these practices. Additionally, a notable portion of farmers (52.5%) stressed the importance of timely distribution of SHCs. Furthermore, it was suggested that SHCs should be available in local and regional languages (Niranjan *et al*., 2018).

Inclusion of additional soil parameters

The current Soil Health Card (SHC) includes essential soil attributes such as macronutrients, micronutrients, pH, electrical conductivity, and organic carbon. However, incorporating additional parameters like soil structure, bulk density, and water-holding capacity would enhance our understanding of soil health. This broader scope would provide valuable insights into the role of soil in improving agricultural productivity and sustainability (Ghosh *et al*., 2018). Soil biodiversity, which encompasses a diverse range of organisms living in the soil, is crucial for maintaining soil health and performing essential functions such as nutrient cycling, organic matter decomposition, and pest control (Wall *et al*., 2012). Incorporating indicators of soil biodiversity into the Soil Health Criteria (SHC) scheme can help protect and enhance soil life, thereby supporting sustainable soil management practices.

Encouraging Public-Private Partnerships

Collaborations between the public and private sectors can significantly enhance the effectiveness of the SHC scheme. By tapping into the expertise, resources, and innovations of private entities, improvements can be made in soil testing, data management, and the development of advanced digital tools and technologies to support efficient soil health management (Mittal *et al*., 2018).

Customization in soil sampling approach

Under the SHC scheme, the cropped area is segmented into 10-hectare grids for rainfed lands and 2.5-hectare grids for irrigated lands. However, this methodology occasionally neglects local soil variability. To remedy this, the sampling approach should be tailored to more accurately capture these variations. Furthermore, it is essential to enhance grid-based soil mapping, as it offers comprehensive soil data for both chemical and natural farming practices by considering the physical, chemical, and biological properties of the soil across different sites within each grid.

Summary

The Soil Health Card (SHC) scheme has emerged as an essential instrument in tackling the challenges of food security in India by promoting sustainable agriculture and enhancing soil health. It has significantly contributed to raising awareness about soil fertility and nutrient management, providing farmers with personalized recommendations to improve soil quality. With the backing of agricultural departments and Krishi Vigyan Kendras (KVKs), SHCs have enabled farmers to increase crop yields and lower cultivation costs by implementing site-specific nutrient management practices. As a result, farmers have seen their net income rise by 30-40%, all while preserving soil health and fertility through integrated farming methods such as reduced tillage, crop rotation, and the use of both organic and inorganic amendments. However, the SHC scheme is not without its challenges, including the need for regular updates and the expansion of soil health monitoring parameters. Enhancing the scheme through digital innovations, capacity building, public-private partnerships,

and improved collaboration will further increase its effectiveness. Keeping farmers informed through regular updates on soil fertility and sharing efficient fertilizer application techniques, such as fertigation and drilling, is vital for better soil management. Additionally, adhering to the recommended fertilizer doses outlined in SHC guidelines has led to reduced input costs, improved soil fertility, and heightened crop productivity. The scheme has also motivated farmers to adopt best practices and seek guidance from agricultural experts. By continually refining the SHC program and broadening its outreach, it can play a significant role in ensuring the long-term sustainability of Indian agriculture, fostering both ecological and economic resilience.

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India's Efforts in Building Climate Change Resilience

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Introduction

Climate change is one of the most pressing global challenges, and its effects are being felt across various sectors, including agriculture, biodiversity, water resources, and human health. India, being one of the most climate-vulnerable nations, faces significant challenges from erratic monsoon patterns, extreme weather events, and shifting agricultural cycles. However, India has undertaken comprehensive measures to adapt to and mitigate climate change impacts. This article explores India's preparedness to tackle climate change, focusing on its policies, research initiatives, and strategies in agricultural resilience.

Climate change is one of the most critical global challenges of our times. Climate change impacts will range from affecting agriculture, further endangering food security to sea level rise and the accelerated erosion of coastal zones, increasing intensity of natural disasters, species extinction, and the spread of vector-borne diseases. Climate change is a global collective action problem and requires international cooperation for its solution. India is a party to the United Nations Framework Convention on Climate Change (UNFCCC), and its Kyoto Protocol (KP), and the Paris Agreement (PA). India is also a party to the Convention on Biological Diversity (CBD) and United Nations Convention to Combat Desertification (UNCCD).

Impact of Climate Change

India's agricultural production and productivity is being impacted by climate change. Changes in precipitation due to erratic monsoon patterns resulting in water scarcity or floods, rising temperatures leading to extreme heat stress, affecting crop development and yields. Climate change can create a more favorable environment for the proliferation of pests and diseases, affecting crop health and productivity. It also led to shifts in the timing of seasons, affecting the sowing and harvesting period of crops and disrupting the traditional agricultural calendars and practices. The production of major food crops like rice, wheat, maize, groundnut, soybean and many pulse crops in the country was affected in the drought years (2002-03, 2004-05, 2009-10 and 2014-15). Similarly, severe floods also affected several field and horticultural crops. Flooding for 24 hours severely affected tomato crop during the flowering stage. Onion during the bulb stage is highly sensitive to flooding. Severe heat wave in north and central India during March-May, 2022 affected the yield of wheat and other horticultural crops. According to the India Meteorological Department (IMD), India faced its hottest February in 2023. High temperature during the flowering and maturity led to loss in yield. A delayed monsoon delayed the sowing of the *kharif* crop in 2023 due to El nino effect.

As part of its 3rd National Communication, the Ministry of Environment, Forest and Climate Change (MoEFCC) conducted studies on impact of climate change in India. Climate change scenarios were analysed using high-resolution regional climate model. Simulations for 2020s, 2050s and 2080s indicate an all-round warming for the Indian subcontinent. Impact of climate change and climate variability on the water resources are likely to affect irrigated agriculture, installed power capacity, environmental flows in the dry season and wet season. Under the NAPCC missions, a number of R&D projects have been supported in climate change studies across India to assess the impact of climate change on coastal vulnerability, health, agriculture and water.

The climate change impact assessment was carried out in different parts of the country by ICAR using crop simulation models by incorporating the projected climates of 2050 & 2080. In absence of adoption of adaptation measures, rainfed rice yields in India are projected to reduce by 20% in 2050 and 47% in 2080 scenarios while, irrigated rice yields are projected to reduce by 3.5% in 2050 and 5% in 2080 scenarios. Climate change is projected to reduce wheat yield by 19.3% in 2050 and 40% in 2080 scenarios towards the end of the century with significant spatial and temporal variations. Climate change is projected to reduce the *kharif* maize yields by 18 and 23% in 2050 and 2080 scenarios, respectively. *Kharif* groundnut yields are projected to be increased by 7% in 2050 scenario whereas in 2080 scenario the yield is likely to decline by 5%. It is also found that future climate scenarios are likely to benefit chickpea with increase in productivity. Projected effects of climate change on rainfed sorghum is reduction of yield by 8% in 2050 scenario. Climate change is projected to impact mustard negatively with seed yields reduction up to 7.9% in 2050 and up to 15% in 2080 scenarios. Soybean yields are projected to increase by 8% in 2030 and 13% in 2080 scenarios.

NAPCC and SAPCC

The Government of India has formulated various schemes that aid in preparedness of the country for increased agricultural production in the country for future changing climate. National Action Plan on Climate Change (NAPCC) was launched by the Indian government on 30th June 2008, which comprises eight National Missions that focus on specific areas of solar energy, energy efficiency, water, sustainable agriculture, health, Himalayan ecosystem, sustainable habitat, Green India, and Strategic knowledge for climate change. NAPCC promotes understanding of climate change, adaptation and mitigation, energy efficiency and natural resource conservation. Thirty-four States /Union Territories (UTs) have prepared their State Action Plans on Climate Change (SAPCC) in line with NAPCC considering the state specific issues relating to climate change. India has also proactively taken a lead in promoting international collaborations through International Solar Alliance and Coalition for Disaster Resilient Infrastructure and has undertaken various programmes and activities through these arrangements. Under the terms of the Paris Agreement, India has submitted its updated Nationally Determined Contributions (NDCs) on 26th August 2022 and submitted its long-term low carbon development strategy on 14th November 2022.

CSS Schemes

The National Mission for Sustainable Agriculture (NMSA) is one of the eight missions within the NAPCC, which aims at evolving and implementing strategies to make Indian agriculture more resilient to the changing climate. It has three major components *i.e.,* Rainfed Area Development (RAD), On Farm Water Management (OFWM) and Soil Health Management (SHM). Subsequently, four new programmes were introduced under the ambit of NMSA namely Soil Health Card (SHC), Paramparagat Krishi Vikas Yojana (PKVY), Mission Organic Value Chain Development in North Eastern Region (MOVCDNER) and Sub Mission on Agroforestry (SMAF). During 2015-16, Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) was operationalized wherein the OFWM component of NMSA was subsumed under Per Drop More Crop (PDMC) component of PMKSY. Additionally, the restructured National Bamboo Mission (NBM) was also launched in April 2018 under the ambit of NMSA. All these schemes enable to promote sustainable and resilient agricultural practices.

The Department of Science & Technology (DST) is coordinating and implementing two national missions, National Mission for Sustaining the Himalayan Ecosystem and National Mission on Strategic Knowledge for Climate Change (NMSKCC), as a part of the NAPCC. Under both missions a large number of R&D projects have been supported in climate change studies to assess the impact of climate change on sectors like Health, agriculture and water and to come up with coping adaptation strategies.

NICRA

To meet the challenges of sustaining domestic food production in the face of changing climate, Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, Government of India launched a flagship network project namely National Innovations in Climate Resilient Agriculture (NICRA) in 2011. The project aims to develop and promote climate resilient agriculture to address vulnerable areas of the country and help the districts and regions to cope up with extreme weather conditions like droughts, floods, frost, heat waves, etc. The project has three components *viz.,* strategic research, technology demonstration and capacity building. The main thrust areas covered are (i) identification of the most vulnerable districts/regions, (ii) development of crop varieties and management practices for adaptation and mitigation and (iii) assessment of climate change impacts on livestock, fisheries and poultry vis-a-vis identification of adaptation strategies.

The NICRA project is implemented across the country in 151 climatically vulnerable districts. It assessed risk and vulnerability of 573 out of 650 predominantly agriculture districts as per Intergovernmental Panel on Climate Change (IPCC) protocol. A total of 109 districts are categorized as 'very high' and 201 districts as 'highly' vulnerable. Adaptation efforts have been underway in 151 out of these 310 (109 + 201) districts through NICRA. Efforts are now underway for conducting risk assessment at sub-district (block) level for the states of Odisha and Maharashtra. District Agriculture Contingency Plans (DACP) were prepared for 650 districts recommending location specific climate resilient crops and varieties and management practices for use by the state departments of agriculture and farmers. These agricultural contingency plans cover weather aberrations like drought (early, mid and late-season droughts), floods, unseasonal rains and extreme weather events such as heat wave, cold wave, frost, hailstorm, cyclone etc. This activity by ICAR in collaboration with State Agriculture Departments will enable preparedness to deal with drought and other weather aberrations.

Some of the most significant research initiatives under NICRA to address the climate change concerns are climate resilient technologies *viz.,* resilient varieties, resilient intercropping systems, conservation agriculture, crop diversification from paddy to other alternate crops like pulses, oilseeds, agroforestry systems, zero till drill sowing of wheat to escape terminal heat stress, alternate methods of rice cultivation (system of rice intensification, aerobic rice, direct seeded rice), green manuring, integrated farming systems, integrated nutrient management, integrated pest management, organic farming, site specific nutrient management, *in-situ* moisture conservation, protective irrigation from harvested rainwater in farm pond, micro irrigation method (drip and sprinkler) etc., have been developed and demonstrated to large number of farmers. Climate resilient varieties have been developed for crops *viz.,* rice, wheat, mungbean, lentil, maize and tomato that are resistant to extreme weather conditions and diseases. These varieties have been introduced in drought and heat wave affected districts, well adopted by farmers resulting in increased crop yields and monetary returns at different locations.

NICRA developed several doable rainfed technologies like rainwater management, efficient and profitable cropping systems, nutrient management, energy management, alternate land use/farming systems which can increase production, decrease cost of cultivation, reduce drudgery and enable farmers to complete farm operations timely. Simulation modelling studies indicate that adopting improved varieties coupled with improved agronomic management practices can minimize the yield loss due to extreme weather events in several crops. Planting methods such as zero till, raised bed planting, cropping intensification with harvested rain water demonstrated in North-Eastern and Eastern states led to 51% yield enhancement.

Under Technology Demonstration component of NICRA, location-specific climate resilient technologies have been tested and validated at on-farm sites of 151 climatically vulnerable districts for adoption by the farmers. One village cluster from each of the 151 districts was selected by the respective Krishi Vigyan Kendra (KVK) in the district and the program is implemented through farmer participatory approach. The technologies developed through active participation of farmers and other stakeholders are ready to be integrated with the developmental programs of different Ministries, so that they reach large number of farmers and secure their livelihood under climate change conditions. During the past twelve years, 21,083 capacity building programs were conducted throughout the country under NICRA project to educate stakeholders on various aspects of climate change and resilient technologies, covering 5,98,529 different stakeholders including farmers so as to enable wider adoption of climate resilient technologies.

Conclusions

Despite contributing minimally to global warming, India has taken significant steps to tackle climate change through robust policies, research initiatives, and on-the-ground actions. By implementing the NAPCC, SAPCCs, and several agricultural resilience programs, India is building its capacity to adapt to and mitigate the impacts of climate change. These efforts are essential for securing the country's future, ensuring food security, and strengthening its agricultural sector in the face of a changing climate. India's proactive approach positions it as a leader in climate action, and with continued innovation, it is on its way to becoming a climate-resilient nation.

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Technological Innovations for Environmental Sustainability

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Agriculture faces unprecedented challenges, including climate change, soil degradation, water scarcity, and the need to feed an ever-growing global population. The global population is projected to grow significantly, reaching 9.7 billion by 2050, up from approximately 8 billion in 2025 (UN, 2024). This rapid population growth will drive a substantial rise in food demand, creating an urgent need for sustainable agricultural practices. According to the Food and Agriculture Organization (FAO), global food production must increase by 70% by 2050 to meet the caloric needs of the expanding population. This translates to producing an additional 1 billion tonnes of cereals and 200 million tonnes of meat annually, a daunting task given the current strain on natural resources. The environmental impact of agriculture is already significant, with the sector accounting for 24% of global greenhouse gas (GHG) emissions, largely due to deforestation, livestock, and fertilizer use (IPCC, 2021). If current practices remain unchanged, emissions are expected to rise in tandem with the increased food production needed to sustain the global population. Additionally, agriculture consumes about 70% of global freshwater resources annually, making it the largest user of freshwater (FAO, 2020). This dependency on water resources exacerbates challenges, especially in regions facing severe water scarcity. Soil degradation is another critical issue threatening agricultural productivity. Over 33% of the world's soil is moderately to highly degraded due to erosion, nutrient depletion, acidification, salinization, and chemical pollution (FAO, 2015). Without addressing these issues, maintaining soil fertility and productivity will become increasingly difficult. In addition to these problems, 30% of all food produced which is approximately 1.3 billion tonnes is wasted each year, contributing to global food insecurity and resulting in 8–10% of global GHG emissions (FAO, 2020). To further exacerbate these challenges, climate change is predicted to reduce global crop yields by 10–25% by 2050 in key agricultural regions, particularly in developing countries. This scenario places even more pressure on agriculture to adapt and innovate sustainably (IPCC, 2021). Fortunately, technological innovations are offering new ways to address these challenges while promoting environmental sustainability. These innovations span various domains ranging from agronomic practices like conservation agriculture and direct-seeded rice to cutting-edge advancements in biotechnology, automation, and renewable energy. Together, these technologies are reshaping agriculture to become more efficient, resilient, and environmentally friendly.

A. Agronomic technological innovations for environmental sustainability

1. Conservation agriculture: a sustainable soil and water management approach

Conservation agriculture (CA) promotes environmental sustainability through three key principles:

- **Minimal soil disturbance**: Reducing tillage preserves soil structure, prevents erosion, retains organic matter, and enhances water retention and fertility.
- **Crop diversification**: Rotating crops, such as cereals and legumes, improves nutrient cycling, reduces pests and diseases, and boosts resilience to climate shocks.
- **Permanent soil cover**: Using cover crops or mulches protects soil from erosion, minimizes evaporation, and enhances organic content and water retention.

By minimizing chemical input dependency and improving soil and water health, CA supports sustainable farming and climate adaptation.

2. Direct-seeded rice (DSR)

DSR is an innovative agronomic practice that enhances environmental sustainability in rice cultivation by conserving water, reducing greenhouse gas emissions, and lowering labour costs.

- **Water conservation**: DSR requires significantly less water than traditional flooded rice systems. Research indicates that DSR can reduce water use by up to 40%, making it particularly beneficial in water-scarce regions.
- **Reduced methane emissions**: Traditional flooded rice fields are substantial sources of methane, a potent greenhouse gas. By eliminating continuous flooding, DSR reduces methane emissions. Studies have shown that DSR can decrease methane emissions by improving root physiological characteristics through better water management.
- **Labor and cost savings**: DSR eliminates the need for labour-intensive transplanting, reducing both labour costs and time. Additionally, fewer tillage operations are required, which helps reduce soil compaction and erosion. This method also allows for more flexible planting schedules, aiding in better crop management.

By adopting DSR, farmers can achieve more sustainable rice production, addressing critical challenges such as water scarcity and greenhouse gas emissions while also benefiting economically (Sandhu *et al.,* 2021).

3. Agroforestry

Agroforestry integrates trees into agricultural landscapes, promoting sustainability through biodiversity enhancement, carbon sequestration, and improved soil health (Raj *et al.,* 2019).

- **Soil erosion control**: Deep tree roots stabilize soil, reducing erosion, especially on slopes, while tree canopies shield the soil from heavy rainfall.
- **Biodiversity enhancement**: Agroforestry creates habitats for wildlife, fostering biodiversity, beneficial insects, pollinators, and natural predators that support crop health.
- **Carbon sequestration**: Trees absorb CO_2, storing it in biomass and soil, helping mitigate climate change and improve soil health.

Agroforestry benefits both the environment and farmers, enhancing resilience, supporting biodiversity, and reducing greenhouse gas emissions.

4. Minimum tillage and no-till farming

- **Soil health improvement**: These practices preserve soil structure, enhance water infiltration, and promote root growth. Soil organisms, such as earthworms and microbes, thrive, supporting nutrient cycling and organic matter buildup.

- **Erosion reduction**: Crop residues left on the soil surface act as mulch, protecting against erosion from wind and water, and maintaining soil fertility.
- **Carbon sequestration**: By increasing soil organic matter, these practices contribute to carbon storage, helping mitigate climate change by capturing CO_2.

These practices support sustainable agriculture, enhancing soil health, water efficiency, and climate change mitigation.

5. Integrated pest management (IPM)

- **Reduced chemical use**: IPM utilizes biological control (e.g., natural predators, biopesticides) and other non-chemical techniques, lowering pesticide reliance and preventing chemical runoff into soil and water.
- **Biodiversity support**: IPM protects beneficial organisms such as pollinators, natural predators, and soil microbes, fostering ecosystem health while controlling pests.
- **Soil health protection**: By reducing pesticide use, IPM safeguards soil organisms essential for fertility, promoting healthier, more resilient soils.

IPM enhances environmental sustainability by reducing chemical inputs, supporting biodiversity, and maintaining healthy ecosystems for sustainable farming.

6. Cover cropping

- **Soil erosion control**: Cover crops provide a protective layer over the soil, reducing wind and rainfall erosion, and preserving soil structure and nutrients.
- **Improved soil fertility**: Leguminous cover crops fix nitrogen in the soil, naturally boosting fertility and reducing the need for synthetic fertilizers while preventing nutrient runoff into water systems.
- **Water retention**: Cover crops enhance soil permeability, helping it absorb and retain water, which reduces runoff and prevents soil degradation during dry periods.

Cover cropping is a simple yet effective practice for enhancing soil health, preventing erosion, and promoting nutrient cycling in sustainable farming systems.

B. Digital technological tools

Technological tools, such as precision agriculture and digital innovations, enhance environmental sustainability in farming by enabling efficient monitoring and decision-making.

- **Soil and crop health monitoring**: IoT sensors and remote sensing technologies provide real-time data on soil moisture, temperature, and nutrients, helping farmers optimize irrigation, fertilization, and pest control, thereby reducing resource waste.
- **Artificial Intelligence (AI) and data analytics**: AI tools analyze large datasets to predict crop yields, optimize planting schedules, and detect potential pest outbreaks, enabling precision decision-making that minimizes environmental impact and boosts productivity.
- **Variable Rate Technology (VRT)**: VRT applies fertilizers, pesticides, and water in precise amounts based on specific field needs, reducing chemical runoff and water waste, while improving both environmental and economic sustainability (Getahun *et al*., 2024).

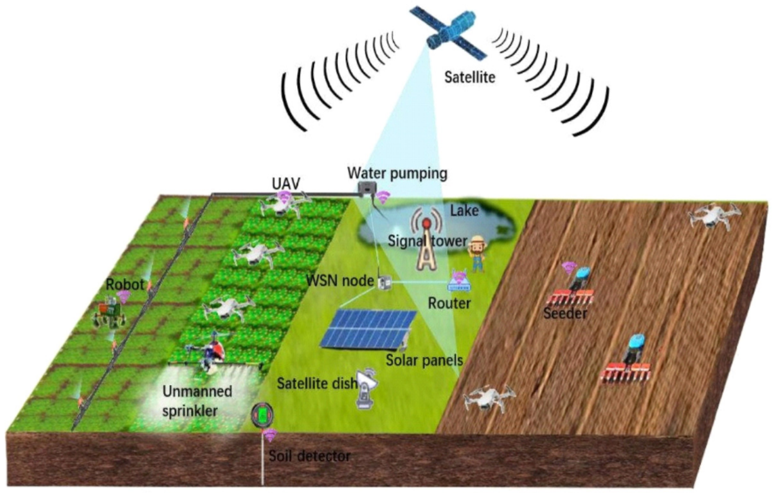

Figure 1. Digital tools for sustainable agriculture

These technologies empower farmers to make data-driven, sustainable decisions, improving resource efficiency and productivity (Fig. 1).

C. Biotechnological innovations

Biotechnology is transforming crop production and sustainability by enhancing crop resilience, boosting yields, and reducing reliance on harmful agricultural practices. Through genetic engineering, crops have been developed to withstand extreme conditions, resist pests, and thrive in poor soils. Key advancements include:

1. **Climate resilience**: Genetically modified (GM) crops, like drought-tolerant maize and flood-resistant rice, help farmers adapt to unpredictable weather patterns. Flood-resistant rice varieties, such as "Sub1," can survive underwater for over two weeks, reducing losses in flood-prone areas.
2. **Reduced agrochemical use**: Crops like *Bt* cotton and *Bt* corn produce natural insecticides, reducing the need for chemical pesticides. This helps decrease environmental pollution and lowers greenhouse gas emissions associated with pesticide production.
3. **Nutritional enhancement**: Biofortification improves the nutritional content of crops to combat food security challenges. For instance, "Golden Rice" is enriched with Vitamin A to address deficiencies in developing countries.
4. **Soil health**: Genetically engineered nitrogen-fixing crops decrease reliance on synthetic fertilizers, preventing soil acidification, and waterway pollution, and maintaining soil fertility.

Overall, biotechnology enables more sustainable farming practices while helping meet the growing food demand of a rising global population.

D. Automation

Automation and precision agriculture are revolutionizing farming by increasing efficiency and sustainability. These technologies, including drones, robotics, GPS-guided machinery, and data analytics, help optimize productivity while minimizing resource waste (Vetrivel and Arun, 2025). Key developments include:

1. **Optimized resource management**: Automated irrigation systems, integrated with Internet of Things (IoT) sensors, monitor soil moisture levels and deliver water precisely where needed. This reduces water wastage and conserves the freshwater resources that agriculture heavily depends on (70% of global freshwater use).
2. **Enhanced efficiency**: GPS-guided tractors and robotic systems ensure accurate planting, fertilizing, and harvesting, which decreases fuel consumption and limits soil compaction. These systems also enable large-scale operations to run more efficiently with fewer resources.
3. **Pest and weed control**: Drones with advanced imaging sensors and AI algorithms detect pest infestations and weed growth early. Targeted spraying systems, like variable-rate sprayers, apply pesticides only in affected areas, reducing chemical use and minimizing environmental impact.
4. **Labor shortages**: Automation helps to address labour shortages by performing tasks such as harvesting, pruning, and seeding quickly and accurately, ensuring consistent productivity even in regions with a declining agricultural workforce.

Automation lowers input costs for farmers, supports sustainable practices, conserves resources, and reduces pollution, driving more efficient and eco-friendly farming.

E. Renewable energy

Agriculture's reliance on fossil fuels for machinery, irrigation, and fertilizer production significantly contributes to global greenhouse gas (GHG) emissions (Kwon *et al*., 2021). Transitioning to renewable energy sources like solar, wind, and bioenergy offers a path to decarbonizing the sector. Key approaches include:

1. **Solar-powered irrigation**: Solar-powered pumps provide an eco-friendly alternative to diesel-driven irrigation systems, especially in off-grid rural areas. They ensure reliable water access while reducing carbon emissions.
2. **Bioenergy from agricultural waste**: Crop residues and animal manure can be converted into biogas and bioethanol, offering renewable energy options (Goel *et al*., 2024). For instance, India's National Biogas and Manure Management Program promotes biogas production from agricultural waste, helping to reduce fossil fuel dependence.

   For environmental sustainability, biotechnology offers solutions to manage greenhouse gases, conserve renewable resources, reduce dependency on non-renewable resources, and restore the environment (Gavrilescu, 2010).

   Agriculture, as a source of renewable energy, can also help to meet global food and fiber needs while providing surplus energy. Several plant species have been modified for biofuel production as an alternative to fossil fuels. First-generation biofuels, produced from sugarcane, maize, and soybean through yeast fermentation into ethanol, allow blending with petroleum fuels to reduce greenhouse gas emissions by up to 42% (Dharani *et al.,* 2024). Additionally, the biofuel industry benefits from innovations in next-generation biofuels, produced more efficiently from plant and algal sources (Fig. 2). Sugar, starch, and lignocellulosic biomass are promising raw materials for biofuel production, offering significant renewable energy potential.
3. **Wind energy for farm operations**: Small-scale wind turbines can power various farm activities, including grain drying and water pumping, especially in regions with consistent wind resources.
4. **Decentralized energy grids**: Farms equipped with renewable energy technologies, like solar panels, can contribute to decentralized energy grids. This reduces energy transmission losses and provides a stable energy supply to rural farming communities.

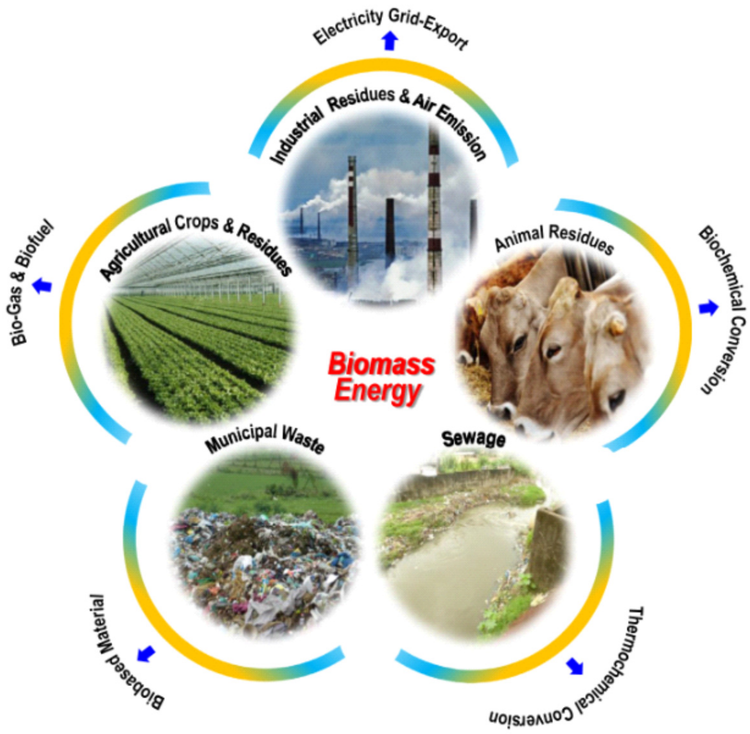

Figure 2. Concept of bioenergy value chain through biomass to biofuels and waste to energy conversion (Dharani *et al.,* 2024)

By incorporating renewable energy into farming systems, agriculture can reduce GHG emissions, lower operational costs, and enhance both economic viability and environmental sustainability.

The integration of agronomic technological innovations, biotechnology, automation, and renewable energy creates a synergistic effect that significantly enhances sustainable agriculture. When combined, these domains offer greater benefits for both efficiency and environmental sustainability. Examples include:

- **Biotechnology-enhanced crops** paired with **automated irrigation systems** powered by **renewable energy** optimize water and nutrient use, minimizing waste and environmental degradation.
- **Automated machinery** for precision farming works seamlessly with **renewable energy systems**, reducing fossil fuel dependence and cutting operational costs.
- **Renewable energy-powered drones** and **AI systems** can optimize pest control and fertilizer application, promoting more sustainable and efficient resource management.

This synergy allows for a more integrated and effective approach to addressing the challenges of modern agriculture, ensuring that farming practices are both productive and environmentally responsible.

Conclusion

Technological innovations play a crucial role in advancing environmental sustainability within agriculture. By embracing technological innovations in agronomic practices, precision farming, sustainable irrigation methods, biotechnology, renewable energy solutions, and digital technologies, the agricultural sector can significantly reduce its environmental impact while simultaneously increasing productivity. However, the widespread adoption of these innovations requires continued investment in research, development, and infrastructure. Policy support is also crucial in ensuring that these technologies are accessible and scalable globally, particularly for smallholder farmers in developing regions. By fostering a collaborative effort between governments, industries, and research institutions, we can achieve a more sustainable and resilient agricultural future that can meet the needs of a growing global population while protecting the planet's natural resources for the next generations.

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Technological Innovations for Sustainable Coastal Agriculture

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ABSTRACT

India's coastal regions, with their vast agricultural potential, face challenges from climate change, salinity, and soil erosion. This article explores sustainable solutions to address these challenges, emphasizing innovative practices and technologies for coastal agriculture. Land shaping methods like ridge-and-furrow systems and farm ponds are pivotal in improving water management and soil salinity reduction. Integrated Farming Systems (IFS) efficiently combine crops, livestock, aquaculture, and forestry, help to enhance productivity and resilience. Climate-resilient technologies, including submergence- and salt-tolerant crop varieties, play a critical role in mitigating environmental risks. Practices like agroforestry and soil conservation ensure ecological sustainability while supporting rural economies. Furthermore, agro-advisory services and community-driven initiatives aid in the dissemination of climate-smart practices. Value addition in agriculture, such as processing coconuts, spices, and tropical fruits, boosts marketability and profitability. Agro-ecotourism leverages local culture and natural beauty to create diversified income streams while fostering environmental stewardship. Through the integration of traditional knowledge, technological advancements, and policy support, coastal agriculture can achieve resilience and sustainability. This synthesis underscores the importance of innovative, climate-adaptive strategies for enhancing food security, protecting livelihoods, and promoting ecological balance in coastal regions.

Key words: Land shaping, Integrated farming system, Climate resilience, Climate resilient varieties

Introduction

India's diverse geography and climatic conditions support a wide range of agro-ecosystems essential for the country's agricultural productivity, biodiversity, and socio-economic development. Promoting tailored innovations, conservation practices, and policy support can ensure the sustainable management of these diverse agro-ecosystems in India. India, with a coastline of 7,516 km, hosts diverse and ecologically significant coastal ecosystems. These ecosystems include mangroves, coral reefs, estuaries, lagoons, backwaters, salt marshes, and seagrass beds. They provide critical ecological, economic, and cultural benefits while being home to unique biodiversity. Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha, and West Bengal are among the coastal states in the region. The climate is humid tropical to subtropical. Rice, legumes, and sugarcane are the main rotation crops in coastal agriculture in low-lying regions. Plantation crops including coconut, areca nut, cashew nuts and cocoa, as well as fruits like mango, banana, pineapple, and guava, and spices like black pepper, ginger, turmeric, clove, and nutmeg, are the main emphasis of horticulture. Among the tuber crops grown are elephant foot yam, sweet potato, and tapioca. Implementing appropriate crop management practices and cropping systems that utilize land and water management can raise productivity and improve the rural economy. Plantation crops can provide raw materials for agro-based businesses, add value, boost export earnings, and diversify product offerings. The industry can gain a great deal from better harvest and postharvest practices of these crops. Because of ample amount of water, coastal aquaculture is growing in productivity despite problems with too much salt in the soil and groundwater. Inland fishing is possible in ponds, lakes, tanks, and rivers. However, only about 45–50% of its potential is produced from these sources. The coastal region's population of sheep, goats, and poultry has steadily increased over time. According to the Central Coastal Agricultural Research Institute (2015) and Mandal *et al.* (2022), the country's east coast has a greater population and genetic diversity in cattle resources than the west coast. The fishing sector plays a significant role in the Indian coastal ecology, with 3432 villages and 8.7 lakh (870,000) families (Central Coastal Agricultural Research Institute, 2015). The water bodies located along the coast provide significant freshwater and marine water fishing opportunities.

The majority of people living along the shore are still employed in the primary sector, which is dominated by smallholder farmers and comprises agricultural, livestock, and fishing farming. Out of all the output sectors, they are the most susceptible to the negative effects of climate change. Climate disasters and the changes that follow have a variety of effects on coastal agriculture. Climate change not only threatens the livelihoods of the primary sector but also has social and economic repercussions. As a result, migration, particularly among young people, has increased in coastal India. Climate change's negative effects are a major concern problem for India, as 85% of farmers lack sufficient financial stability. This presents a serious risk to the food and livelihood security of the area. Farmers have employed a range of adaptation strategies to reduce the effects of climate change and maintain their livelihoods. Both farmer-led and endorsed adaptation solutions are possible. The former are created by farmers based on their experiences, while the latter are suggested to farmers by organizations. Additionally, in varying periods and situations, the adaption strategies impact farmers' transformative, adaptive, and absorptive capacities in constructing a resilience

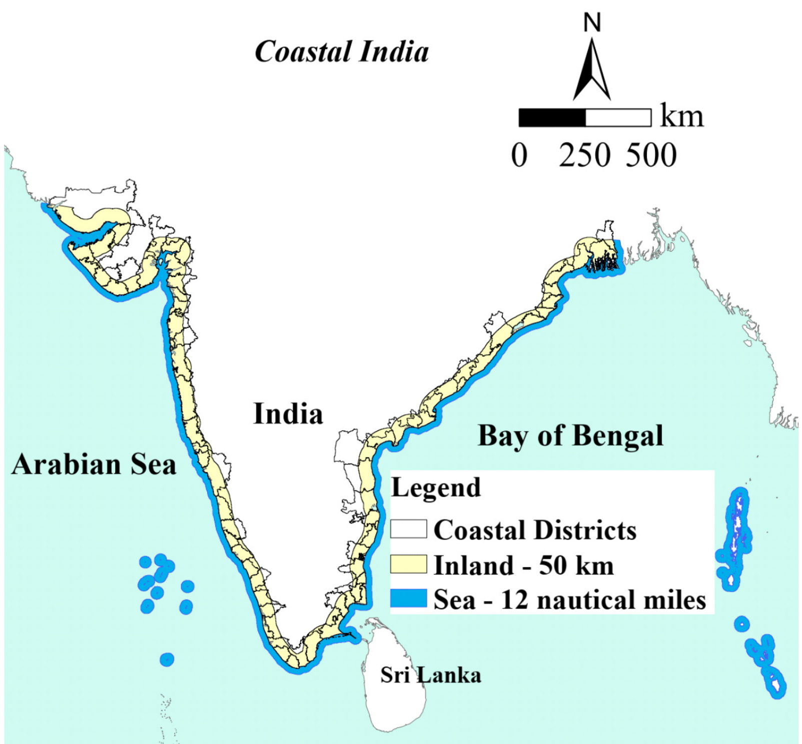

Figure 1. Coastal region of India

pathway (Bhattacharyya *et al.*, 2020). Additionally, it is thought that sustainable agriculture practices could include social equality, economic viability, and ecological integrity—the three pillars of sustainability. Technology can improve productivity and quality of life by being used in an integrated coastal systems research management plan.

Technologies available for coastal region of India

The foundation of a farm's economy is healthy soil and water. However, these two sectors can be regarded as the most impacted because of the climate change in India's coastline region. The soil and water of the area is seriously threatened by the frequent occurrence of tropical storms, flooding, and sea level rise. However, the issue has been made worse by salt intrusion's indirect effects, which include imposing soil salinity, causing soil erosion, and degrading freshwater bodies. The lack of freshwater and groundwater, the spread of diseases transmitted by water, an outbreak of pests and diseases, and the decline in soil fertility and yield are only a few of the long-term consequences of this. Therefore, it is imperative to consider adaptation strategies that aim to restore, safeguard, and preserve soil and water ecosystems from the consequences of climate change.

Land shaping

Land shaping is a process that involves modifying the surface of the land to create various types of land, such as highlands, lowlands, and ridgelines (Burman *et al.*, 2013). It can be utilized to increase land productivity, mitigate the effects of salinity and waterlogging, and generate irrigation supplies. Land contouring can help improve drainage congestion, reduce the impact of brackish groundwater tables, diversify and produce crops year-round, combine agriculture, aquaculture, and animal farming, improve the productivity and livelihood security of farming communities. Land shaping is a method of changing land to reduce salinity. Improved irrigation, drainage, and freshwater management can help farmers adapt to climate change.

Farm pond (FP)

Approximately 20% of the agricultural field is converted into a 3m-deep pond to collect excess rainwater. The dug-out soil is used to generate high land/dike and medium land conditions on the farm, allowing for year-round crop development rather than relying solely on rice during the *Kharif* season. The pond collects rainwater for irrigation and pisciculture. Poultry and animal farming can be carried out on the farm with crops and fish, using pond water. Crop, fish, cattle, and poultry integrated farming is both environmentally and economically beneficial. Integrated crop-fish-livestock/poultry-duckery farming encourages environmental sustainability and effective nutrient management on farms. The high land is ideal for year-round crop cultivation due to the absence of waterlogging in *Kharif* and low salinity levels in the dry season.

Deep furrow and ridges (DF)

Approximately 50% of farmland is converted into alternate ridges (1.5 m top width × 1.0 m height × 3 m bottom width) and furrows (3 m top width × 1.5 m bottom width × 1.0 m depth). Ridges are formed by using the soil from furrows. Because of the higher elevation and rainwater accumulation in furrows, these ridges are less prone to waterlogging during *Kharif* and have lower soil salinity throughout the dry season. The furrows are used for more profitable paddy cum fish farming in *Kharif*. Rainwater collected in furrows is used for irrigation. During the dry season (*Rabi*/summer), land without furrows or ridges is utilized to grow low-water crops like cotton and groundnuts. The ridges are utilized to grow vegetables and other horticultural crops all year, rather than just rice during *Kharif.* Furrows gather rainwater, which keeps the root zone soil wet in the dry months after *Kharif*. This reduces the flow of brackish water from the shallow subsurface layer, lowering soil salinity levels. Furrows promote drainage and protect crops from the effects of heavy rains and climatic changes throughout *Rabi*/summer. This approach can help to increase productivity in coastal saline soils with poor drainage. The reduced impact of soil salinity benefits poor coastal farmers by increasing their income, livelihood security, and employment opportunities.

Medium ridge and shallow furrow (SF)

Approximately 75% of the agricultural land is split into medium-sized ridges (1.0 m top width × 0.75 m height × 2.0 m bottom width) and furrows (2.0 m top width × 1.0 m bottom width × 0.75 m depth), with a 3.5 m spacing between each ridge and furrow. During *Kharif*, the furrows are used for paddy + fish cultivation and rainwater collection, much like in DF. The cropping schedule is similar to that of DF, with the distinction that rice can be grown in furrows during the summer and *Rabi* seasons, requiring less supplemental irrigation.

Paddy-cum-fish (PCF)

To protect the free flow of water from the field and improve the amount of rainwater collected, trenches (3 m top width × 1.5 m bottom width × 1.5 m depth) are constructed around the farmland's perimeter, leaving an outer border of around 3.5 m width. The dugout soil is utilized to build dikes measuring 1.5 m top width, 1.5 m height, and 3 m bottom width. When the water in the trenches runs out, a small ditch is built in one corner of the field to provide shelter for fish. Vegetables are planted on the dikes year-round. The remaining farmland, including trenches, is used for more profitable paddy and fish farming during *kharif*. During the dry (*Rabi*/summer) seasons, the land (non-trench and non-ridge region) is used to grow crops that require less water, with rainwater gathered in trenches. Deep ditches improve field drainage conditions during non-monsoon months. Because brackish water is abundant (ground or river water) nearby, the site is also suitable for profitable brackish water fish farming during the dry season. Suppose the brackish water is pumped out (required for fish harvesting) and the land is allowed to wash off the salts with a couple of the heavy pre-monsoon showers that are common in the area. In that case, the land can be used again for paddy-cum-fresh water fish cultivation in *Kharif* (Burman *et al*., 2013).

Soil and water conservation techniques

Soil conservation approaches seek to preserve the top fertile soil. Liming can help to minimize soil acidity, a common issue in coastal areas in addition to salinity. Leaching with good quality water, applying gypsum, increasing tillage, summer ploughing, and FYM can assist to manage problem soils like salinity and sodicity. Ponds and tiny bodies of water are important sources of freshwater for agriculture and other purposes in coastal regions. Furthermore, they can be used for homestead fishing, enhancing food security in the region. Pond salinization not only has a direct impact on the ecosystem, but also poses a long-term threat to its use.

Continuous contour trenching combined with vetiver grass as a vegetative barrier can minimize soil loss by 47.8% and runoff by 44.5% in cashew (Mahajan *et al*., 2021). Erosion can be controlled using engineering methods such as bunding, trenching, drainage line treatment, and water harvesting structures. Vegetative barriers made of grasses and bamboo can assist in stabilizing slopes in the mining region. Soft methods such as sand dune rehabilitation, green belts, geo-tubes, and geotextile sand containers can help to reduce sand erosion. The irrigation system plays an important role in soil and water management approaches. Coastal farmers, particularly smallholders, rely on freshwater sources such as rivers and ponds for irrigation. Natural calamities like cyclones and floods can lead to increased salinity, compromising the irrigation system. Gravity-based irrigation can be achieved using rainwater harvesting ponds located on hilltops. Environmentally friendly wastewater treatment plants can help to reduce pollution. Investments in irrigation infrastructure, such as storage facilities and distribution networks, can help to fulfill rising water demand. Availability of fresh water for drinking is a big issue in coastal areas because of the saline conditions. Saline water is found in the majority of tube and open wells along the shore. One practical solution to the drinking water problem is rainwater harvesting. Rainwater overhead tank construction is expensive, and marginal farmers cannot afford it. Additionally, the tank can only hold a certain amount of water. Rainwater can be collected from residential roofs using PVC pipes and a pressure tank buried in the ground. The harvested water can then be collected by a basic piston pump or engine and mixed with saline water.

Integrated Farming Systems (IFS)

The agricultural system is a complex interconnection of soil, plants, animals, implements, power, labor, capital, and other inputs controlled by farming families. It is also influenced by political, economic, institutional, and social influences at many levels. Farmers have created and maintained particular agricultural systems based on species diversity, traditional methods, and advanced management approaches.

Integrated farming systems (IFS) have two main characteristics: 1) waste or by-product utilization, whereby the wastes or by-products of one subsystem are used as inputs to a second subsystem; and 2) improved space utilization, whereby the two subsystems effectively occupy all or a portion of the space needed for a single subsystem.

The IFS is a sophisticated and comprehensive approach to sustainable agriculture in which various agricultural components such as crops, livestock, aquaculture, agroforestry, and renewable energy sources are combined to improve productivity, resource efficiency, and ecological balance. The IFS model emphasizes the interdependence of its components, guaranteeing that waste from one activity is used as an input in another, lowering external input costs and decreasing environmental effects. The primary goals IFS are to: 1) integrate natural resources and regulatory mechanisms into farming operations to provide the greatest possible replacement of off-farm inputs; 2) ensure sustainable production of high-quality food and other products using environmentally friendly technologies; 3) maintain farm income; 4) eliminate or reduce sources of current agricultural pollution; and 5) maintain the various functions of agriculture (Kumar and Paramesha 2021).

(i) Resource optimization

One of the fundamental ideas of IFS is the efficient use of available agricultural resources, such as land, water, and organic waste, in order to maximize productivity while reducing external inputs. By using strategies such as resource recycling, nutrients within the system are successfully reused,

Table 1. Sustainable IFS models in the east and west coast of India with multiple benefits (Ravisankar *et al*., 2016)

District	Sustainable farming system model	Production (kg)	Marketable Surplus (kg)	Profit (Rs)	Employment (man-days)
Srikakulam (Andhra Pradesh)	Field crops + dairy + goat + poultry	5867	3600	35582	360
Bhubaneswar (Odisha)	Cropping system + horticultural system, dairy + poultry + fishery + boundary plantation + kitchen garden + apiary	25472	21459	123167	449
Thanjavur (Tamil Nadu)	Crops + dairy + poultry + horticulture + fishery + vermi compost + boundary plantations	55456	50450	323167	460
24- South Parganas (West Bengal)	Field crops + dairy + fishery	11854	8950	38500	288
North Goa (Goa)	Field crops + dairy + fish + poultry birds	25490	22354	126750	255
Karamana, (Kerala)	field crops + horticulture (fruits and vegetable crops) + dairy + poultry	19414	14816	102545	209
Pathinamthitta (Kerala)	Field crops + horticulture (fruits and vegetable crops) + dairy + poultry	34616	33845	34616	369
Karjat (Maharashtra)	Field crops + horticulture + livestock + composting	49780	42750	192168	370
Raigad (Maharashtra)	Field crops + livestock + kitchen garden	11628	9607	65708	412

Figure 2. Integrated Farming System models

preserving soil fertility and lowering reliance on fertilizers. This closed-loop technology improves resource efficiency while simultaneously reducing the environmental impact of farming methods.

(ii) Diversity and synergy

The integration of various farming components fosters complementary connections, resulting in increased productivity and resource usage. For example, integrating aquaculture and paddy cultivation increases water efficiency and promotes nitrogen cycling. This interconnection ensures that one component's outputs serve as inputs for another, resulting in a balanced and self-sustaining ecosystem on the farm. The interaction of diverse components promotes mutual benefits, minimizing waste and increasing overall agricultural output.

(iii) Economic stability

IFS supports revenue diversification by incorporating a variety of industries, including crop production, livestock husbandry, aquaculture, and agroforestry. This diversification decreases the financial risks connected with crop failure and market price changes, providing farmers constant income. Furthermore, by recycling farm resources and reducing external input requirements, IFS reduces production costs, hence increasing economic resilience and profitability.

(iv) Environmental sustainability

IFS aims to promote environmental stewardship through waste recycling and sustainable resource management. Composting crop wastes and employing livestock manure in biogas units reduce pollutants while increasing soil fertility. IFS also promotes soil and water conservation methods, such as agroforestry and drainage system development, to counteract erosion, salinity, and waterlogging. By preserving ecological balance, IFS promotes long-term sustainability and resilience to environmental problems.

Improved livestock management

As previously noted, the smallholder farming community in the coastal region relies on a variety of enterprises to make their livelihood. One of the most significant of these is the livestock sector. The livestock sector not only generates revenue for farmers, but also provides food security. Due to climate change, regional temperature increases of 2 to 3°, followed by an increase in relative humidity, can intensify the heat stress in animals, resulting in a decrease in milk production, a loss in reproductive capability, and a significant slowing of their growth. A managed microenvironment optimizes temperature, humidity, and air circulation. This protects the health, output, and general well-being of animals against the negative effects of heat-induced stress. Research has revealed a number of strategies farmers have used to create a microclimate in the shed, including employing electric fans or coolers with cross ventilation. Other methods identified in the evaluation for creating a climate-proof livestock shelter including concrete shed, raising the cow shed just above the ground to guard against flood damage, and creating two-tiered, storm-resistant housing for poultry. To preserve the shed's microclimate, locally accessible materials like coconut leaves and paddy straw were used to cover the roof.

Feeding is a critical component of livestock management, with proper food and nutritional strategies play a key role in mitigating the effects of heat stress. Research indicates that maintaining an appropriate feeding regime can help to minimize productivity losses and weight reduction in animals caused by stress. To address this, farmers should increase the quantity of feed, including both roughages and concentrates, during stressful periods. Heat stress, which triggers behavioral and metabolic changes in animals, typically results in reduced feed intake and energy shortages. To counteract this, farmers may use supplements such as common salt, mineral mixtures, calcium, and proteins. Additionally, heat stress causes significant water loss through sweating, prompting farmers to ensure a consistent supply of fresh, clean drinking water and implement practices like regular bathing or sprinkling water on animals. In coastal regions of India, farmers may also adopt feeding schedules to the local climate, avoiding mid-day feeding during hot summer months to prevent restlessness in animals. Instead, they feed livestock during cooler parts of the day or at night, ensuring that heat production from digestion does not coincide with peak temperatures. To further support livestock during heat stress, farmers may adopt strategies such as altering feeding and grazing times and providing smaller, more frequent meals instead of bulk feedings. However, climate change poses additional challenges, such as disruptions in forage availability, particularly in straw-dependent coastal areas. To address these issues, farmers may take steps like planting multi-purpose fodder trees, which offer a sustainable solution to the growing problem of fodder insecurity caused by irregular climate patterns.

Climate-resilience technologies

Climate resilience is defined as the ability to anticipate, respond to, and recover from climate-related events, trends, or disturbances. Climate resilience is crucial because climate change is a global issue that has local consequences. A comprehensive climate action program must include resilience activities at the person, neighborhood, and asset levels. Climate resilient agriculture (CRA) refers to the adoption of adaptation, mitigation, and other techniques in agriculture that improve the system's ability to respond to diverse climate-related disturbances by preventing harm and recovering rapidly. Coastal zones account for about 2% of the earth's area yet house more than 10% (600 million people) of the total population (Neumann *et al.*, 2015), and as a result, coastal ecosystems are among the most damaged and altered globally (Adger *et al.*, 2003). To lessen the vulnerability of coastal agriculture systems, resilient agroecosystem stewardship solutions must be developed. Agro-ecosystem stewardship refers to the responsible use and protection of the agricultural system through conservation and sustainable practices, whereas "resilience-based agroecosystem stewardship" emphasizes resilience as a fundamental feature of the changing world, as well as agro-ecosystems that provide a suite of ecosystem services rather than a single resource. To address some of the complex challenges posed by climate change, agriculture (including livestock and fisheries) must become "climate-smart," which means increasing agricultural productivity and incomes sustainably, adapting and building resilience to climate change, and reducing and/or eliminating greenhouse gas emissions wherever possible (FAO, 2013a). CSA is defined as a method of altering and reorienting agricultural development to reflect the new realities of climate change (Lipper *et al.*, 2014). It is classified as "agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces Green House Gases (GHGs) where possible, and enhances achievement of national food security and development goals" (FAO, 2013b).

CSA practices can be implemented in coastal areas to help reduce the impacts of climate change on food security and livelihoods, which includes (i) crop diversification: increasing the diversity of crops or varieties grown in an area; (ii) sustainable soil management: channeling the expansion of crop and grazing land to reduce carbon loss; (iii) improved water management: using strategies to improve water management; (iv) agroforestry: using trees to provide shade and other benefits; (v) coastal afforestation: planting trees along the coast to protect crops from strong winds and reduce erosion; (vi) community-based buffer zones: establishing buffer zones along the coast to reduce the impact of tropical cyclones; (vii) seaweed farming: farming seaweed to increase carbon removal from the atmosphere; (viii) mangrove protection: protecting mangrove forests and estuaries to conserve biodiversity and reduce erosion.

Agro-advisory services

Timely information on the weather forecast and farm advises could be a viable approach to avoid crop losses and improve the poor crop yield and ultimately the farmers income. To provide real-time weather forecasts and agro-advisories at a block/taluka level to the farming community Agro-Meteorological Field Units (AMFUs) and District Agro-Met Units (DAMUs) were set up by India Meteorological Department (IMD) in collaboration with the Indian Council of Agricultural Research (ICAR). The advisories are compiled in the form of weather-based agro-advisory bulletins twice a week which is every Tuesday and Friday. Wider and effective dissemination are achieved through bilingual bulletins published in English and local language of the region. A framework of reaching out of advisories to farmers at village and block levels is also achieved through various information and communication technologies (ICTs). Awareness and capacity building programmes are also conducted to make the farmers aware about these services. Agro-advisory services enable farmers to save crops from aberrant weather and plan timely agricultural operations.

Traditional extension methods (such as face-to-face interactions, demonstrations, field days, printed materials, etc.), information and communication technologies (ICTs) (radio, cell phones, video, social media), rural resource centers, farmer-to-farmer extension, and farmer field schools are just a few of the ways that can help to increasing agricultural productivity sustainably to support equitable increase in farm incomes, food security, and development. Experts in climate change, for instance, can benefit from rural advisory services (RAS's) experience in fields like information distribution through ICTs. Although extension workers are often responsible for sharing knowledge and technology, RAS providers encounter difficulties developing and promoting climate-resilient practices and technologies.

The uncertainties and risks associated with climate change can be managed by adapting and enhancing the resilience of agricultural and food security systems to climate change at multiple levels. To diversify agriculture and income options and become more resilient, farmers need to draw on local and scientific knowledge, sharpen their observational and experimental skills and improve their critical thinking and problem-solving abilities to be able to make their own decisions about appropriate practices and diversified and resilient income opportunities from a menu of options.

Climate resilient varieties

Climate-resilient crop varieties are pivotal in addressing the challenges faced by coastal agriculture, including salinity, submergence, and extreme weather events. These varieties enhance productivity and safeguard the livelihoods of farmers while promoting sustainability in fragile ecosystems. In coastal regions, flooding is one of the most frequent natural disasters caused by cyclones and tidal inundations. Farmland close to the beach gets flooded for a while because of poor drainage. Submergence-tolerant cultivars are at the forefront of yield stability protection because they possess genetic traits that allow them to withstand conditions of waterlogging. Farmers believed that one of the most successful farming technologies was the cultivation of the submergence-tolerant paddy type (Swarna Sub-1). It is anticipated that this variety would produce favorable yield impacts when fields were submerged for seven to fourteen days. Submersion tolerance paddy varieties with high yielding capacity and good grain quality are MTU-1061, RGL-2537, Pratiksha, and CR 500. Salinity is a major concern in relation to flooding and submergence conditions, and farmers in the coastal region have reportedly adopted salinity-tolerant varieties. The use of indigenous salt-tolerant varieties was a long-standing practice, especially in the country's eastern coastal region, but it was gradually replaced by high-yielding varieties after the green revolution. Salinity-tolerant paddy varieties have been reintroduced to improve climate-resilient agriculture, and these include Nona-bokra, Talmugur, Lal Getu, Sada Getu, Darsal, Lunishree, and Gosaba, as well as CARI Dhan, Usar Dhan-5, Jarava, Geetanjali, SR-26B, and Amalmona. Over time, diseases and pests have become more prevalent as a result of climate change, causing farmers to suffer significant losses. Farmers regarded PDM54 (green gram) and PU 30 (black gram), two disease-resistant pulse varieties, as key scientific crop farming innovations. The development of short-duration cultivars has also grown significantly in importance given the current climate environment. Crop calendar adjustment has become a well-liked sustainable farming technique, as previously said. Cultivars with short lifespans help prevent abiotic problems like drought and flooding. It also makes it possible for farmers to plant a second crop that will grow quickly, increasing farm income and promoting income diversification. The significance of climate resilient varieties in sustaining the dynamic nature of climate resilience is substantial. Adopting disaster-resistant and short-duration cultivars helps to increase farm profitability and adaptability. It also enables the successful application of other sustainable agriculture practices.

Agro-ecotourism

Agro-ecotourism in coastal areas holds significant potential to enhance the livelihoods of local farmers, diversify the rural economy, and promote sustainable development while preserving cultural and ecological heritage. This form of tourism integrates agricultural and ecological experiences, allowing visitors to explore rural life, sample authentic local cuisine, and gain hands-on insights into traditional and modern farming practices. Beyond economic benefits, agro-ecotourism fosters deeper community connections, encourages cultural exchange, and helps safeguard intangible cultural assets, such as traditional crafts, ethnic music, and folklore, which might otherwise fade away. For tourists, it offers a refreshing escape from the hustle and bustle of daily urban life, providing opportunities to relax and rejuvenate amidst serene natural settings. The combination of scenic landscapes, farm-to-table culinary experiences, and participatory agricultural activities creates a holistic, enriching experience that appeals to a wide audience, from families and students to eco-conscious travelers.

However, for this emerging industry to thrive sustainably, strategic planning, scientific research, and collaboration among stakeholders-including farmers, local communities, policymakers, and tourism operators are essential. (Kumar and Paramesha, 2021) propose a framework for agro-ecotourism development that prioritizes livelihood security and ensures that the benefits are equitably distributed among local communities. By providing a platform for selling traditional and ethnic products, offering jobs, and developing tourism-related services, agro-ecotourism can serve as a

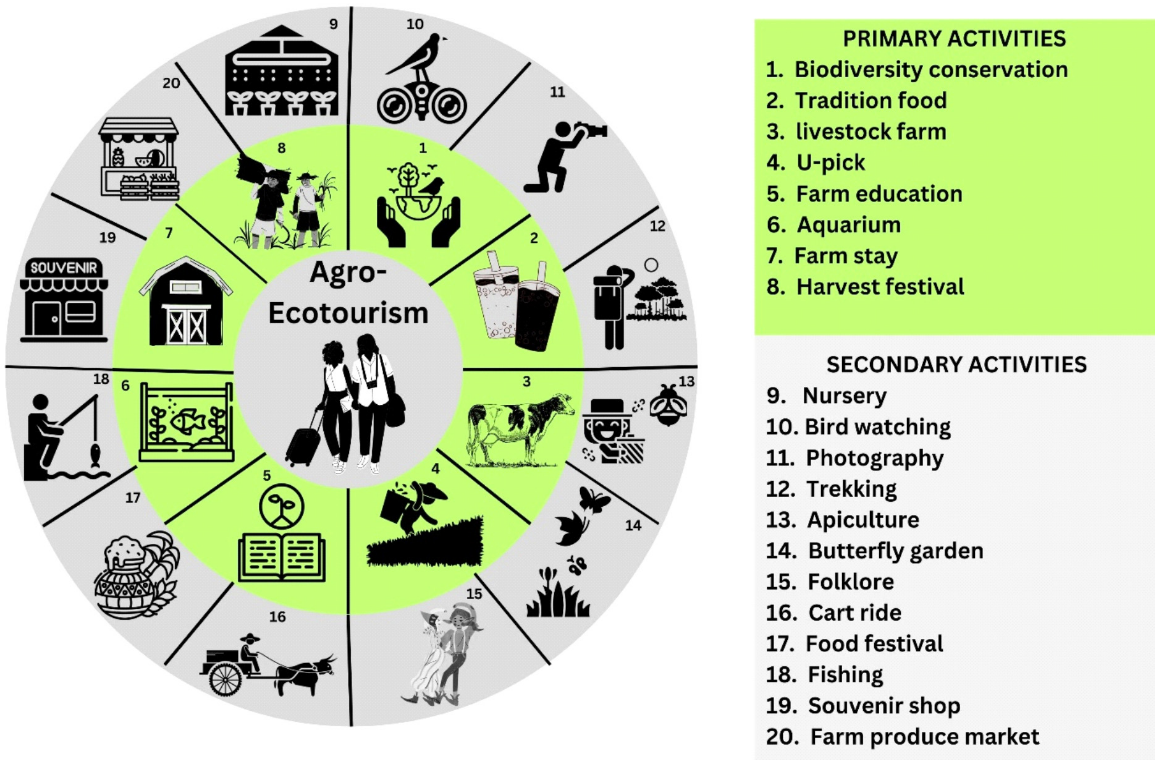

Figure 3. Elements of Agro- ecotourism

powerful tool for rural economic empowerment. Furthermore, it encourages sustainable land-use practices and environmental stewardship, ensuring that the natural and cultural resources underpinning this industry remain intact for future generations. Overall, agro-ecotourism represents a harmonious blend of economic development, cultural preservation, and ecological sustainability, making it a vital component of rural revitalization strategies in coastal and other rural areas.

Value addition in the agricultural sector

Value addition in coastal areas is essential for promoting sustainable agriculture, enhancing economic returns, and building resilience against climate change. In these region, innovative processing techniques such as solar drying, freeze-drying, and eco-friendly packaging significantly improve the marketability and shelf life of tropical fruits, spices, and coconuts. For instance, premium organic products like aromatic rice, tropical beverages, and processed coconut derivatives cater to high-value domestic and international markets. Marine resources also contribute to value addition; for example, seaweed can be processed into biofertilizers or health supplements, and fisheries can produce high-value products like dried or pickled fish. These innovations align with sustainable practices, ensuring resource efficiency and environmental preservation. By integrating such approaches, coastal agriculture not only enhances livelihoods but also contributes to environmental sustainability and economic diversification.

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Empowering Resilient Farming in Eastern India: Agro-physical Techniques for Climate-Adaptive Agriculture

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ABSTRACT

In the face of increasing climate variability, Eastern India, with its diverse agro-ecological zones, faces significant agricultural challenges. Extreme weather events, erratic rainfall, and rising temperatures threaten agricultural productivity, particularly for small and marginal farmers. To mitigate these effects and ensure sustainable farming, resilient farming systems incorporating agrophysical techniques are essential. In this context, various agrophysical techniques, including mulching, conservation tillage, agri-voltaic systems, shade nets, windbreaks, polyhouses/ greenhouses and precise nutrient and water management can significantly improve farm resilience in Eastern India. These techniques, by optimizing soil moisture, regulating microclimates, conserving water, and improving resource use efficiency, offer practical solutions for adapting to the challenges posed by climate change. Through the integration of such practices, Eastern India's farming systems can adapt to climate extremes, improving agricultural productivity, sustainability, and profitability.

Introduction

Agriculture today is confronted with an unprecedented array of challenges stemming from climate change, resource scarcity, and the increasing demand for food security. The concept of resilient farming systems has emerged as a critical approach to address these challenges and ensure sustainable agricultural productivity. Climate change, primarily driven by the rising atmospheric concentration of greenhouse gases, presents a significant threat to global agriculture. According to projections by the Indian Meteorological Department, the warming of winter months in India will be more pronounced compared to the rainy season. Additionally, rainfall patterns are expected to become more erratic, characterized by fewer rainy days with higher intensity rainfall events. This combination of rising temperatures and water stress poses serious implications for crop production, particularly in tropical regions.

The agricultural sector in India is vulnerable to climate variability, with small and marginal farmers bearing the brunt of its adverse impacts. Resilient farming systems refer to agricultural practices that can withstand environmental shocks and stresses while maintaining productivity, profitability, and sustainability. Eastern India, characterized by its diverse agro-ecological zones, is particularly susceptible to climate variability. The region experiences frequent weather extremes, including cyclones, floods, droughts, heatwaves, and cold spells. These extreme weather events adversely affect agricultural productivity, necessitating the adoption of resilient farming practices to ensure food security and sustainable livelihoods in the region.

To address these challenges, agrophysical techniques offer practical solutions by modifying the microclimate around crops to mitigate the adverse impacts of climate variability. In this regard, agrophysical techniques such as mulching, tillage practices, agri-voltaic systems, shade nets, windbreaks, polyhouses/greenhouses etc have gained prominence in promoting resilient farming systems. These techniques are particularly relevant to the agricultural landscape of eastern India, where erratic rainfall, extreme weather events, and increasing temperatures pose significant risks to crop production. Agrophysical techniques leverage physical principles and technologies to create favourable conditions for crops, addressing challenges posed by climate variability. The following are key agrophysical techniques relevant to resilient farming systems in eastern India:

Mulching

Mulching, a vital practice in resilient farming systems, involves covering the soil surface with organic or inorganic materials to optimize soil health, improve water use efficiency, and enhance crop productivity. In the face of climate variability and resource constraints, mulching serves as a sustainable solution to mitigate the adverse impacts of environmental stressors on crops.

Several studies have highlighted the role of mulching in improving crop yields and water use efficiency — key components of resilient farming. A significant increase in the grain and straw yield (Mohammad *et al*. 2012) of wheat and higher water use efficiency of maize (Iqbal *et al*. 2008; Yaseen *et al*. 2014) with crop residues retention have been reported demonstrating its potential to conserve water resources in semi-arid and water-scarce regions. Wang *et al*. (2012) further emphasized that reduced tillage combined with residue incorporation led to increased water use efficiency in maize, supporting the integration of mulching with conservation agriculture practices. Kumar and Lal (2012) explained how mulching modifies the microclimate by regulating soil temperature and moisture levels, directly influencing wheat yield and resilience to weather fluctuations.

Types of mulch

Organic mulch: Organic mulches such as straw, grass clippings, crop residues, and wood chips are widely used to improve soil health and fertility. These materials decompose over time, adding essential nutrients to the soil and enhancing its water-holding capacity. In resilient farming systems, organic mulch plays a dual role in maintaining soil moisture and improving soil structure, making it particularly beneficial in rain-fed and drought-prone areas.

Inorganic mulch: Inorganic mulches, including plastic films and geotextiles, are used primarily for moisture conservation, temperature regulation, and weed suppression. These mulches are especially effective in high-value vegetable and fruit crop production systems. In resilient farming, the use of biodegradable plastic films can further enhance sustainability by reducing environmental impacts.

Benefits of mulching in building resilience

Mulching provides numerous benefits that contribute to the development of resilient farming systems as shown in Figure 1.

- *Water conservation:* By reducing soil evaporation, mulching helps maintain consistent soil moisture levels, thereby decreasing the need for frequent irrigation. This is critical in regions facing erratic rainfall patterns and limited water availability.

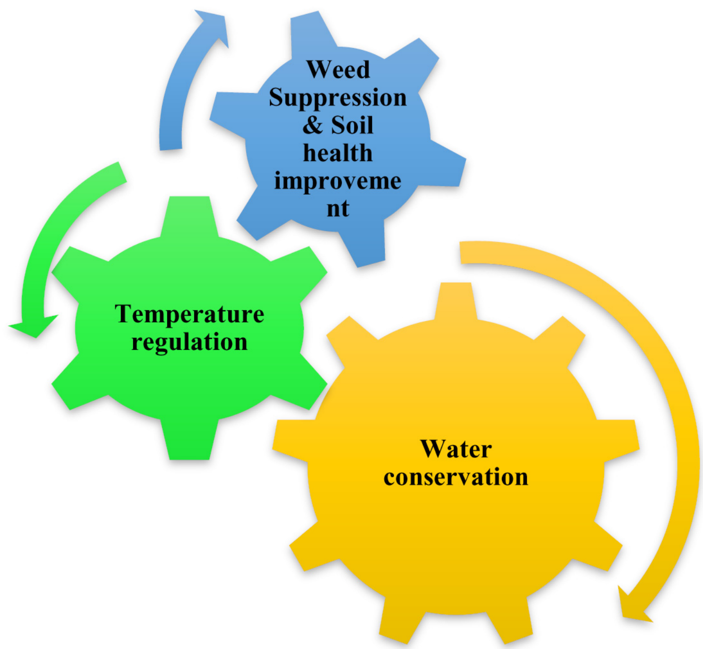

Figure 1. Benefits of mulching

- *Temperature regulation:* Mulch acts as an insulating layer, keeping the soil cooler during hot weather and warmer during cold spells. This microclimate modification protects crops from extreme temperatures and supports stable growth.
- *Weed suppression:* Mulch minimizes competition for water, nutrients, and sunlight by preventing weed growth, thereby reducing the reliance on herbicides and manual labor.
- *Soil health improvement:* Organic mulches enrich the soil with organic matter, improving soil structure, microbial activity, and overall fertility. This enhances the soil's ability to retain moisture and withstand periods of drought.

Incorporating mulching into farm management practices not only increases water use efficiency but also promotes resource conservation, making it an essential component of climate-resilient agriculture. As water resources become increasingly scarce and climate uncertainty grows, mulching offers a practical and cost-effective strategy for ensuring long-term agricultural productivity and sustainability.

Conservation tillage

Conservation tillage, a proven strategy for enhancing soil health and promoting climate-resilient farming, involves minimal soil disturbance, retention of crop residues, and the integration of cover crops. This approach improves soil structure, water infiltration, and organic matter content, all of which help mitigate the negative impacts of climate variability.

Research suggests that conservation tillage practices significantly improve soil porosity and aggregate stability (Oliveira *et al.*, 2019). Moreover, long-term adoption of reduced tillage increases soil shear strength, particularly in the upper soil layers, which is essential for reducing soil erosion and improving water retention (Feiza *et al.*, 2015; Steponavièienë *et al.*, 2023). These practices are crucial for enhancing the resilience of rain-fed agricultural systems and reducing vulnerability to extreme weather events.

Incorporating conservation tillage into climate-resilient farming systems not only improves soil health but also enhances long-term sustainability by reducing the vulnerability of farming systems to extreme weather events. These practices help maintain soil moisture, increase carbon sequestration, and reduce the risks associated with climate change, ultimately contributing to improved productivity, farm profitability, and resilience to future climatic challenges.

Land shaping

Land shaping techniques are crucial for improving rainwater harvesting and its effective utilization in agriculture. By modifying land contours and incorporating dugout ponds, rainwater can be efficiently stored and used to support various farm activities. This stored water provides essential irrigation during dry spells, while also enabling farmers to diversify their livelihoods through integrated practices such as fish and duck rearing.

This approach maximizes the use of available resources, enhances productivity, and ensures continuous agricultural activities throughout the year. Moreover, integrating farm system with rainwater harvesting boosts resilience against climate variability, increases farm income, and fosters sustainable agricultural practices in resource-limited areas. Sikka *et al*. (2017) underscored the advantages of rainwater harvesting through farm ponds and community tanks in rainfed districts, enhancing resilience and cropping intensity (20–135%). The construction of temporary check dams (bori-bandhan) in high-rainfall areas facilitated the cultivation of previously fallow lowland areas, which would otherwise have been submerged during the kharif (monsoon) season. Additionally, renovating aahar (water reservoirs) and building farm ponds in Bihar provided protective irrigation during dry spells in kharif, resulting in a 20.7% increase in paddy productivity and a 30 cm rise in the groundwater table.

Agri-voltaic systems (AVS)

Agri-voltaic systems (AVS), an effective agrophysical technique for resilient farming in eastern India, optimize land use by integrating photovoltaic (PV) solar panels with crop production as shown in figure 2. By providing partial shading, AVS modifies the microclimatic conditions beneath the panels, reducing heat stress, minimizing evaporation, and stabilizing soil temperatures. This improves water-use efficiency and reduces moisture stress, which is critical for managing extreme weather variability in the region. Studies by Prakash *et al*. (2023) and Othman *et al*. (2020) confirm

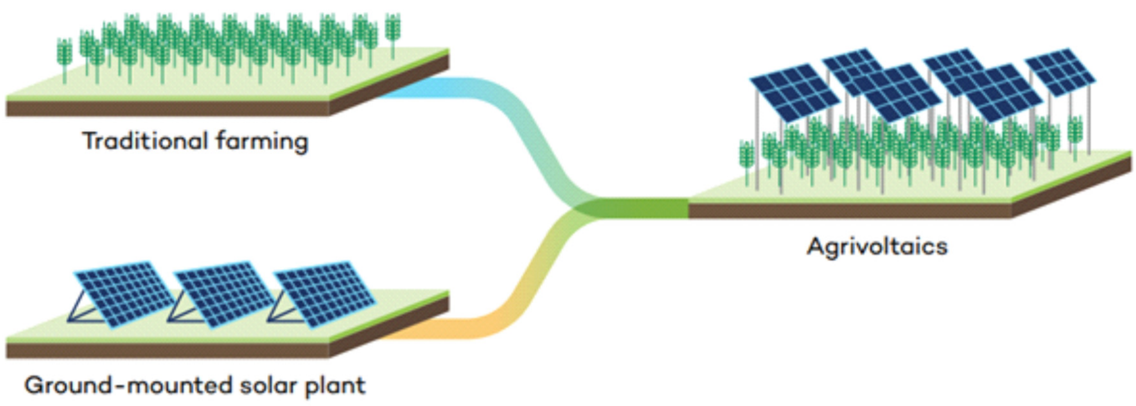

Figure 2. Illustration of typical Agri-voltaic system

that AVS enhances crop performance in such conditions, making it a sustainable solution for energy generation and climate-resilient agriculture.

Agri-voltaic systems (AVS) offer multiple benefits for the agricultural region of eastern India, including states like Bihar, West Bengal, and Odisha, which are highly vulnerable to extreme weather events like floods, droughts, and cyclones. AVS can help conserve water by reducing soil evaporation, which is crucial in areas with fluctuating water availability. Additionally, the integration of photovoltaic (PV) panels on agricultural land allows farmers to generate renewable energy, reducing reliance on conventional power sources and providing energy for irrigation and farm equipment. AVS also provides opportunities for income diversification, as farmers can sell surplus solar energy to the grid, enhancing economic resilience. Furthermore, elevated PV panels can act as protective barriers against floods, reducing soil erosion and protecting crops from waterlogging.

Shade Nets

Shade nets are a valuable agrophysical technique for resilient farming in eastern India, particularly for vegetable, flower, and nursery crops. By reducing direct sunlight based on crop-specific needs, shade nets create a favorable microenvironment with higher relative humidity, lowering evapotranspiration and conserving water. Research by Sharma & Singh (2016) highlights their role in protecting crops from heatwaves and enhancing photosynthetic efficiency by minimizing photoinhibition. This makes shade nets an effective solution for managing weather extremes and improving crop productivity in the region's variable climate.

Windbreaks and shelterbelts

Windbreaks and shelterbelts, consisting of rows of trees or shrubs, are effective agrophysical techniques for resilient farming in eastern India. They protect crops from strong winds, reduce wind speed on the leeward side, and help minimize soil erosion. Studies by Burke (1998) and Campi *et al*. (2009) show that windbreaks reduce crop evapotranspiration, making them particularly beneficial in dryland and semi-arid farming systems. In eastern India, windbreaks can protect cereal crops, orchards, and plantations from wind damage, enhancing crop resilience in the region's variable climate.

Polyhouses and greenhouses

Polyhouses and greenhouses provide controlled environments that protect crops from climatic challenges such as heavy rains, frost, hailstorms, and strong winds. Polyhouses, made from translucent polythene, are cost-effective for small-scale farmers, while greenhouses made from glass or polycarbonate materials offer more durability and precise environmental control. These structures trap heat during the day and reduce excessive cooling at night, ensuring a stable temperature range for crops. However, the environmental impact of polyhouses and greenhouses must be considered, with studies suggesting the use of Artificial Intelligence (AI) to optimize energy use and reduce the carbon footprint (Mayuri *et al*., 2024).

Agrophysical innovations

The adoption of innovative agrophysical techniques like precision nutrient management and smart water management systems is also essential for climate-adaptive agriculture in Eastern India.

By synchronizing nutrient and water management with crop needs and leveraging digital tools and sensor-based technologies, farmers can build resilient farming systems that are better equipped to withstand climatic uncertainties. These climate-smart agricultural practices are not just a necessity but a sustainable solution for ensuring food security in the face of climate change.

Precise nutrient management

Precision nutrient management enhances fertilizer use efficiency by applying nutrients in the right form, amount, and timing, synchronized with the crop's nutrient demand, and at the appropriate location. Tools for precision management of nitrogenous fertilizers include Leaf Color Charts, chlorophyll meters, and optical sensors like GreenSeeker (Purba *et al*., 2015). Decision support systems, available on computer or Android mobile platforms, such as Nutrient Expert and Crop Manager, also assist farmers in the precise management of nutrients (Pampolino *et al*., 2012).

Smart water management techniques

Micro-irrigation systems, including micro-sprayers, trickle, or drip irrigation, are highly efficient techniques for delivering water directly to the root zones of crops. These systems have been shown to reduce irrigation water usage by 20–48%, energy consumption by 10–17%, labor costs by 30–40%, and fertilizer usage by 11–19%, while simultaneously improving Agricultural Crop Productivity (ACP) by 20 to 38% (PMKSY 2019). These localized irrigation methods not only play a crucial role in conserving water but are also essential for saving energy (Shah, 2009) and reducing carbon emissions. Furthermore, the adoption of solar-powered drip irrigation systems can further contribute to water and energy conservation, as well as the reduction of carbon footprints. In addition to micro-irrigation, pressurized irrigation systems coupled with sensor-based irrigation scheduling (such as tensiometers, gypsum or resistance blocks, Frequency Domain Reflectometry (FDR), and Time Domain Reflectometry (TDR)) hold significant potential for improving crop water productivity in resilient farming systems (Abhilash *et al*. 2021). Wireless sensor arrays are also increasingly used for real-time irrigation scheduling, further enhancing precision in water management. These advanced agrophysical techniques represent critical adaptation strategies for mitigating the effects of climate change, improving resource efficiency, and increasing the resilience of farming systems to climatic uncertainties.

Role of agrophysical techniques

Agrophysical techniques offer several advantages in building resilient farming systems:

- *Enhanced crop resilience:* By mitigating the effects of heatwaves, frost, and strong winds, these techniques ensure consistent crop growth and yield.
- *Water conservation:* Techniques such as mulching and shade nets reduce water requirements, promoting sustainable water use.
- *Extended growing seasons:* Controlled environments enable year-round cultivation, improving profitability.
- *Improved resource efficiency:* By optimizing light, temperature, and humidity, microclimate regulation reduces input wastage.

Conclusions

Empowering resilient farming in Eastern India through the adoption of agrophysical techniques is crucial in addressing the challenges posed by climate change. These techniques offer practical and sustainable solutions to combat the impacts of climate variability on agriculture. By incorporating practices such as mulching, conservation tillage, land shaping, and agri-voltaic systems, farmers can boost agricultural resilience, ensuring long-term productivity, profitability, and environmental sustainability. These practices help mitigate the adverse effects of climate change while promoting sustainable livelihoods and food security in the region. Through the integration of agrophysical techniques into farm management, farmers can increase productivity, conserve valuable water resources, and strengthen the agricultural sector's resilience. Additionally, diversifying cropping systems and utilizing precision farming methods allow farmers to adapt to changing climatic conditions, reduce risks, and optimize resource use. Ultimately, these strategies not only enhance farm productivity but also foster the long-term sustainability of agriculture, ensuring food security and rural prosperity amidst the uncertainties of a changing climate.

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Nurturing Health and Qualities of Indian Soil: Challenges and Strategic Solutions

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In India, a great body of literature exists in soil research in regards to physical, chemical and biological properties of soils. However, in most of these researches, the parameters were studied in isolation with respect to their influence on crop productivity irrespective of their roles in performing various soil functions. Assessment of soil degradation has been made and well documented in India. But its operational aspects linking to crop production and upkeeping soil and environmental quality have hardly been addressed. Database generation for key indicators of soil quality, are therefore, essentially required for different soil types, cropping systems, and management practices under various agro-ecoregions of the country for quick assessment of soil health with a view to identifying aggrading/degrading production systems.

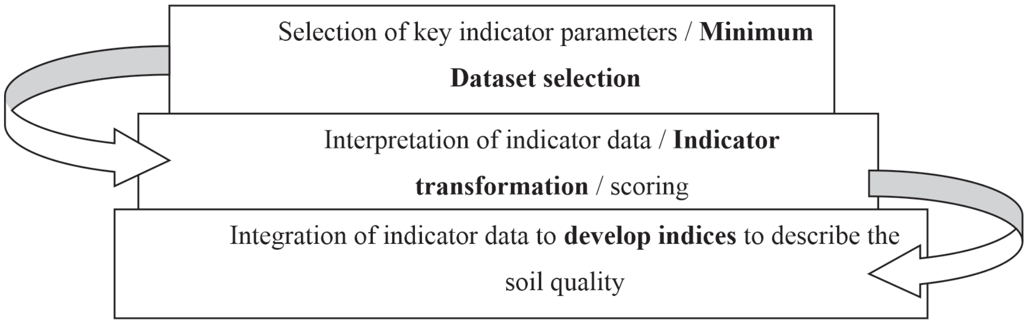
Soil Quality Assessment Framework

Framework for evaluating soil quality has been developed involving integration of physical, chemical and biological functions with indicators that emerge at the systems/process level. Indicators for soil quality assessment have been identified for major soil types/eco-regions/management practices in a few developed countries with threshold values for a few systems. Several workers have made efforts for identifying indicators for assessing quality of soils within certain boundary conditions using several statistical techniques of which use of principal component analysis has been recognized as an important tool.

Despite the importance of SQI in describing SQ degradation or aggradations, there is no universally accepted dataset selection, scoring, and SQ indexing method for field conditions. Previous studies reported that different methods of minimum dataset selection (MDS), scoring, and SQ indexing have been applied but SQI results varied even for the same conditions. The most widely reported MDS methods of SQ indicators are expert opinion and statistical tools (e.g., regression, principal component analysis (PCA)). An expert can generate a list of appropriate SQ indicators on the basis of ecosystem processes and functions and other decision rules such as management goals for a site associated with soil functions as well as other site-specific factors, like region or crop sensitivity as selection criteria (Andrews *et al.*, 2004).

Key steps in soil quality evaluation

Soil quality evaluation is accomplished through the following three key steps:

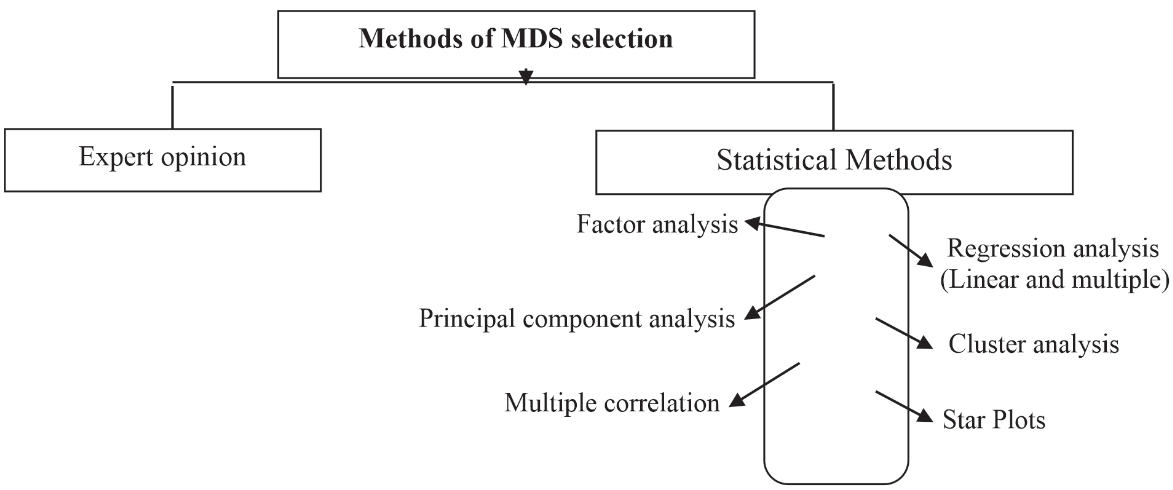


Selection of Minimum dataset (MDS)

The selection of key or representative indicator parameters which best describe the system under study, is the first and the most critical step in soil quality study. The soil quality or the capacity of soil to function should be reflected by the indicator parameters, otherwise known as soil quality indictors (SQIs). Selecting a group of such indicators forms the minimum dataset for comparative or dynamic assessment of soil quality. As proposed by Doran and Parkin (1994), the selection of MDS should fulfill the following criteria:

- Integrate soil physical, chemical and /or biological properties and processes
- Should be applicable under diverse field conditions
- Complement either the existing database or easily measurable data
- Respond to land use, management, climate and human factors

The MDS selection is achieved by several methods, the prominent among them are



Several MDS have been proposed on the basis of expert opinion (EO), Till date, the EO method is most commonly used for MDS selection. This requires expert knowledge about the soil functions and the systems to be studied. However, it suffers from disciplinary biases.

Scoring or indicator transformation

The transformation of the datasets into scores (scoring function) can be done using linear and nonlinear scoring techniques. Linear scoring can be used and may be desirable for indicators that change gradually along a continuum. In the NAIP sub-project, each MDS indicator was transformed using a linear scoring method (Andrews *et al.*, 2002). Indicators were arranged in order depending on whether a higher value was considered ''good'' or ''bad'' in terms of soil function. For 'more is better' indicators, each observation was divided by the highest observed value such that the highest observed value received a score of 1. For 'less is better' indicators, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of 1.

Integration of scores into indices

In NAIP sub-project, the MDS variables for each observation were weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, divided by the total percentage of variation explained by all PCs with eigenvectors >1, provided the weighted factor for variables chosen under a given PC. The weighted MDS variables scores for each observation were then summed up using the following equation:

$$SQI = \sum_{i=1}^{n} WiSi$$

where, S is the score for the subscripted variable and Wi is the weighing factor derived from the PCA. Here the assumption is that higher index scores meant better soil quality or greater performance of soil function. Further, the percent contribution of each final key indicator was also calculated. The SQI values so obtained (hereafter called PCASQI) were tested for their level of significance at P = 0.05. Since weighing factor for each indicator is derived from PCA carried out by the four centers, the numerical value of "weightage" is different. Hence SQI value obtained in one agro-ecosystem cannot be compared with the same numerical value of SQI obtained in other agro-ecosystem.

The summary of the computation of SQI (PCASQI) of different soils and cropping systems based on the identified indicators in NAIP sub-project is presented in table 2. In spite of uniform scoring of the identified indicators in 0-1 scale, the numerical values of SQI differed widely depending on the soil type and cropping system (Table 1). This could be attributed to the variation in number of PCA derived indicators and different numerical value of the weightage factor obtained from PCA. Because of these reasons the SQI value of a particular soil-cropping system is non-comparable with the SQI value of other soil-cropping system. The computation of SQI (PCASQI) values derived from PCA were validated in terms of the yield potential of the cropping systems, as measured by % relative yield of the cropping systems. Here, % relative yield indicates the ratio of the observed yield (combined yield of both the crops in rotation in terms of equivalent yield) of any site divided by the maximum yield obtained in a particular study area. It was observed that the measured SQI values (PCASQI) provided quite a satisfactory indication about the productive potential of the cropping system (Table 1).

Thus, the results suggest that the PCA derived soil quality indicators and subsequent computation of SQI for a given soil-cropping system together with productive potential of the cropping systems could be used to indicate the overall health of the soil and any increase or decrease in this numerical value of SQI would indicates aggradation or degradation of the overall health of the soil.

Table 1. Summary table of soil quality index based on key indicators derived from PCA

Name of the AESR	Soil Types	Cropping Systems	Soil Quality Index Range	Soil Quality Index Mean	% Relative Yield of the Cropping System (Mean)
AESR 4.1	Entisol	Rice-WheatMaize-Wheat	0.972-1.005 0.982-1.05	0.92±0.10 1.00±0.11	64.20 68.54
	Inceptisol	Rice-Wheat	0.768-0.936	0.87±0.12	82.19
AESR 7.2	Alfisol	Monocropped with Paddy, Cotton, Castor, Redgram, Maize etc.	0.257-0.719	0.44±0.09	42.25
	Inceptisol	Monocropped with Paddy, Cotton, Castor, Redgram, Maize etc.	0.345-0.727	0.50±0.09	60.18
	Vertisol	Monocropped with Paddy, Cotton, Castor, Redgram, Maize etc.	0.172-0.703	0.46±0.11	58.58
AESR 10.1	Vertisol	Soybean-WheatPristine soil	0.894-1.809 1.512-1.982	1.22±0.15 1.67±0.09	56.82 -
AESR 15.1	Inceptisol	Rice-Potato-Sesame (Harit Series)	0.37-0.80	0.60±0.13	75.33
		Rice-Potato-Sesame (Baligori Series)	0.55-0.82	0.68±0.08	78.05
		Rice-Rice (Harit Series)	0.66-0.89	0.77±0.07	73.73
		Rice-Rice (Baligori Series)	0.24-0.76	0.51±0.18	76.06
	Alfisol	Rice-Potato-Sesame (Kataban Series)	0.51-0.86	0.67±0.13	84.42
		Rice-Potato-Sesame (Bulanpur Series)	0.47-0.77	0.66±0.10	81.55
		Rice-Rice (Kataban Series)	0.22-0.78	0.42±0.18	68.19
		Rice-Rice (Bulanpur Series)	0.72-1.49	1.06±0.27	76.22
		Rice-Wheat (Kataban Series)	0.58-0.69	0.62±0.05	75.52
		Rice-Wheat (Bulanpur Series)	0.51-0.93	0.71±0.18	79.40

Soil Quality Rating

Assessment of soil health in terms of Soil Quality Index derived from principal component analysis is a tedious and cumbersome job. In order to simplify the assessment protocol of soil health, NAIP sub-project used the concept of Relative Soil Quality Index (RSQI) based on fifteen soil indicators comprising of three physical indicators, two biological indicators and ten chemical indicators. Based on this approach of rating soil health using uniform scoring and weightage values, the health of soils of eight targeted districts were classified into poor category (soils having RSQI values <50%), medium category (soils having RSQI values 50-70%) and good category (soils having RSQI values >70%). As per this approach, none of the soil in AESR 4.1 and AESR 15.1 was found in poor category, whereas, 50% soils in an AESR 7.2 was found in poor category. In the Vertisol region of AESR 10.1 about 16.7 and 4.2% of the soils of Vidisha and Sehore districts were found to be in poor category, respectively. In AESR 4.1, majority of the soils (around 75%) belong to medium category whereas 25% soils were found to have good soil health. In this region, the observed mean relative yield (%) of the medium category soils ranged between 62.4-81.2 while it was 85.2-86.8% in case of good category soils. In AESR 7.2, the soils under good category were found to range between 1.3-1.9%. Because of different crops were grown in this region, no relationship between RSQI and crop yield could be established (R^2 =0.145). In AESR 10.1, about 78% of the soils were found in medium category and the observed mean relative yield of crops ranged between 50.2-58.2%. In this region, 16.7 and 4.2% soils of Vidisha and Sehore districts were categorized as poor soils , respectively, while 5.7 and 18.3% soils were found to be of good category soil. The observed mean relative yield under poor and good category soils varied from 39.8-53.9% and 74.5-78.2%, respectively. In AESR 15.1, none of the soils in Hoogly and Bankura districts was found in poor category. Based on this classification, 100% soils in Hoogly district was found in good category, while about 78% soils of Bankura district was found in good category soils. However, marked difference was observed in terms of productive capacity of the good category of soils of Hoogly and Bankura districts. Thus, the results showed that this approach of rating of soil health based on RSQI concept may be an useful tool and there is need of more extensive investigations to validate its usefulness for assessment of soil health.

Soil-Test-Based Fertilizer Recommendations: Targeting Yields, Sustaining Soil Health

Ramamoorthy *et al.* (1967) established the theoretical basis and experimental proof for the fact that Liebig's law of the minimum operates equally well for N, P and K. This forms the basis for fertilizer application for targeted yields. Ramamoorthy *et al.* (1967) have refined the procedure of fertilizer prescription as given by Truog (1960) and later extended to different crops in different soils. This provides a scientific basis for balanced fertilization not only between fertilizer nutrients but also with the soil available nutrients (Dey, 2012; Dey and Santhi, 2014; Dey, 2016). Targeted yield concept strikes a balance between 'fertilizing the crop' and 'fertilizing the soil'. The procedure provides a scientific basis for balanced fertilization and balance between applied nutrients and soil available nutrients. The linear relationship between yield and uptake implies that for ob-taining a given yield, a definite quantity of the nutrient must be taken up by the plant. This is also borne out by the near constancy when the response is expressed in the form of units of grain production per unit of nutrients absorbed by the plant. It is the reciprocal of this form, *viz*., response to absorbed nutrient which is expressed as nutrient requirement in kg/q of grain production. It has been observed that the nutrient re-quirement per quintal of grain pro-duction is nearly the same for a given variety although variations be-tween varieties of crop and in the same variety between -two different seasons (Kharif versus Rabi) have been observed.

For a given soil type-crop-agro--climatic condition, the essential ba-sic data required for formulating fertilizer recommendation for targeted yield are: (i) nutrient require-ment in kg/q of produce (grain or other economic part); (ii) the per cent contribution from the soil available nutrients; and (iii) the per cent contribution from the applied fertilizer nutrients. The above men-tioned three parameters can be deduced from the soil test crop response experiments. The resultant fertilizer adjustment equations have been tested in follow up and frontline demonstrations conducted in different parts of the country. In these trials soil test based rates of fertilizer application helped to obtain higher response ratios and benefit: cost ratios over a wide range of agro-ecological regions (Dey and Srivastava, 2013, Majumdar *et al*., 2014).

The targeted yield approach is unique in developing soil-test-based fertiliser prescriptions for desired yield target chosen by the stakeholders based on their input use capability. It also provides the fountain to decide nutrient ratios for development of customised fertilisers. Determination of basic data for targeted yield needs further refinement efforts. In particular, the problems of low values for per cent efficiencies of soil and fertilizer nutrients that is encountered in some instances, need to be improved by identifying the factors responsible for this, which could lead to further scope for development of improved cultural and fertilizer management practices for enhancing nutrient utilization efficiencies.

Targeted Yield-Based Fertilizer Recommendations for maintenance of soil health

Fertilizer recommendation for realizing in the short term greater fertilizer use efficiency on the one hand and far maintenance of sail fertility in the long term an the other seem to have two opposing dimensions. If soil fertility is to be main-tained or even increased, heavier doses of fertilizers have to be used to take into account the inevitable lasses in the availability due to lea-ching and fixation. Therefore, to get the best out of fertilizer investment, the turnover from it must be very quick. This is ensured when fertilizers are applied far law yield targets. Under such situations, the excess na-tive soil nutrient (S) will make a great contribution to increase the yield. This would mean low doses of application of fertilizer and exhaust-ing of the unutilized excess nutrients from the soil. The soil fertility would, therefore, deplete at a faster rate as a result of this exhaustion. Thus, these two approaches seem to be pulling in different directions and it will be necessary to adjust the fertilizer practices over seasons in such a way so as to strike a balance bet-ween the two.

The generation of basic data for targeted yield of crops in a rotation would enable application of fertilizer far appropriate yield targets so that over seasons, the twin objectives of high yields and maintenance of soil fertility (Table 2 and 3) could be achieved (Dey and Gulati, 2013). Singh *et al*. (2015, 2017, 2018) also found beneficial effect of STCR based nutrient application on soil health under different cropping systems. Kumar *et al*. (2021) also found beneficial effect of long-term application through STCR approach over other mode of manures and fertilizer application in Pearl Millet [*Pennisetum glaucum* (L.)] – Wheat [*Triticum aestivum* (L.)] cropping system of semi-arid North-West India.

Table 2. Changes in bulk density, water retention and hydraulic conductivity of soil in guar- wheat cropping system under Rajasthan condition

Treatment	Soil depth (cm)	Bulk density		Water retention (%)						Hydraulic conductivity (cm/hr)	
		Y_i	Y_3	Y_i (10 kPa)	Y_3 (10 kPa)	Y_i (33 kPa)	Y_3 (33 kPa)	Y_i (1500 kPa)	Y_3 (1500 kPa)	Y_i	Y_3
Control	0-15	1.52	1.53	8.80	8.77	5.60	5.58	1.90	1.88	10.4	10.51
	15-30	1.53	1.53	8.60	8.61	5.30	5.28	2.10	2.08	8.2	8.23
General	0-15	1.52	1.52	8.80	2.82	5.60	5.63	1.90	2.11	10.4	10.32
recommendation dose (GRD)	15-30	1.53	1.53	8.60	8.62	5.30	5.34	2.10	2.18	8.2	8.16
STCR	0-15	1.52	1.52	8.80	8.88	5.60	5.81	1.90	2.21	10.4	10.28
	15-30	1.53	1.53	8.60	8.69	5.30	5.42	2.10	2.36	8.2	8.11
STCR-IPNS	0-15	1.52	1.50	8.80	9.51	5.60	6.36	1.90	2.89	10.4	9.28
	15-30	1.53	1.50	8.60	9.22	5.30	6.07	2.10	2.51	8.2	7.76

$Y_{i:}$ Initial; Y_3: After 3 years

Table 3. Changes in soil microbial biomass, dehydrogenase activity and organic carbon in guar- wheat cropping system under Rajasthan condition

Treatments	Soil depth (cm)	Microbial biomass (mg kg^{-1})		Dehydrogenase activity (P K at/g)		Organic C (%)	
		Y_i	Y_3	Y_i	Y_3	Y_i	Y_3
Control	0-15	30 ±6.0	20 ± 3.2	1.05	1.06 ±0.06	0.11	0.07 ± 0.02
GRD (without organics)	0-15	30 ±6.0	40 ± 5.4	1.05	2.10 ±0.07	0.11	0.10± 0.03
STCR (without organics)	0-15	30 ±6.0	53 ± 5.5	1.05	2.88 ±0.07	0.11	0.12 ± 0.03
STCR-IPNS	0-15	30 ±6.0	69 ± 6.3	1.05	3.93 ±0.07	0.11	0.19± 0.03

$Y_{i:}$ Initial; Y_3: After 3 years

Linking Soil Health Testing with Management Practices

Managing for soil quality will enhance soil resilience, and resilient soils respond to management (Lal 1998). Management practices that increase soil organic matter levels will improve most soil functions. In normal conditions, the soil can maintain equilibrium by pedogenetic processes. However, this equilibrium is easily disturbed by anthropogenic activities (e.g., agricultural practices, deforestation, and overgrazing). In order to make sound decisions regarding sustainable land use systems, knowledge of SQ related to different land use scenarios is essential. It is therefore most important to assess SQ degradation of different land use and soil management systems using soil quality index (SQI) since many of the factors that influence sustainable productivity are related to SQ. Information on SQI can support to further prioritization and then device management strategies that improve soil resources sustainably.

Way forward

The development of effective policy frameworks for sustainable soil management and climate-resilient agriculture necessitates a multi-faceted approach, including land governance, extension services, advisory support, access to finance and markets, and local governance models. Monitoring and evaluation across all stages of agricultural production are crucial to ensuring the successful implementation of these strategies (Dey, 2020). The adoption of advanced soil sensing technologies and the Agricultural Internet of Things (AIoT) offers transformative potential for sustainable agriculture. Proximal soil sensors, such as hand-held devices and vehicle-mounted systems, enable rapid, real-time analysis of soil properties, including nutrient availability and elemental composition (Dey and Bhattacharyya, 2021). These tools overcome the limitations of traditional soil testing by reducing costs, improving efficiency, and providing site-specific data essential for precision farming. Advanced technologies like laser-induced breakdown spectroscopy (LIBS) and ion-sensitive field-effect transistors (ISFETs) further enhance soil analysis by delivering high-resolution, multi-element insights directly in the field (Erler *et al.*, 2020). Complementing these are nanosensors and smart delivery systems, which monitor and optimize irrigation and nutrient application, ensuring efficient resource use. Integration of satellite imagery and remote sensing technologies, exemplified by platforms like Climate FieldView™ and SoilOptix, facilitates precise fertilizer recommendations tailored to specific field areas, promoting sustainable soil management and enhanced crop health.

AIoT extends these capabilities by integrating sensors, drones, and remote sensing tools into interconnected systems for comprehensive farm management. The portability and flexibility of AIoT components allow precise characterization of field variability, supporting variable-rate technology (VRT) for targeted input application (Taylor *et al.*, 2019). This minimizes resource wastage, reduces operational costs, and enhances productivity. By leveraging digital agriculture technologies such as AI, machine learning, and cloud computing, farmers can make data-driven decisions, optimize inputs, and adapt to climate-resilient practices (Dey, 2019). Effective policy frameworks, combining land governance, extension services, and big data analytics, are critical to institutionalizing these innovations. Emphasis on organic residues, alternative nutrient sources, and dynamic recommendations ensures holistic nutrient management. Collectively, these strategies promise a future of sustainable farming, resilient ecosystems, and thriving agricultural communities.

Conclusion

Soil quality has become an internationally accepted science-based tool for advancing the assessment, education, understanding and management of soil resources. Two of the most important factors associated with the soil quality concept are that (1) soils have both inherent and dynamic properties and processes and that (2) soil quality assessment must reflect biological, chemical, and physical properties, processes and their interactions. In general, SQI is a useful assessment tool that may help in soil conservation and resource management apart from assessments of soil erosion and changes in productivity. SQI can thus provide the necessary information for planners and decision makers to make informed decisions against SQ degradation using the introduction of appropriate interventions. Despite such importance of SQI in combating SQ degradation, only few studies have been reported in relation to various land use and soil management systems. This indicated that research on SQI has been mostly neglected for unknown reasons, with the most probable reason which could be technical and financial limitations. Adoption of targeted yield approach provides the scientific basis for balanced fertilization not only between the fertilizer nutrients themselves but also that with the soil available nutrients for sustaining soil health.

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Role of Smart Tools in Sustainable Water Resource Management

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ABSTRACT

Water is considered as elixir of life and it is vital for crop production as it plays important role in plant metabolic pathways like photosynthesis, respiration, nitrogen metabolism etc. This necessitates agricultural sector to depend heavily on water resources availability and their management. Unfortunately, we have been witnessing the decline in water resources in the recent years which is quite alarming. Hence, we must emphasize on optimal utilization of available water resources with highest precision at critical time period i.e. precision water management. In other words, we need to concentrate on research and capacity building on smart tools for sustainable water management. This article discusses on present scenario of water resource availability and status, prospects and strategies of precision water management and description of some successful smart tools for sustainable water resource management.

Key words: Precision water management, Smart tools, Sustainable water resource management

Introduction

The food security in India is mainly challenged by the diminishing water resources in agriculture coupled with ever increasing human population. Further, the changing climate further worsens the scenario. Extreme climatic events have been witnessed at higher frequency now. Owing to extreme events, the crops are subjected to either excess water stress or deficit water stress. This necessitates us to minimize the damage to agricultural sector in the backdrop of changed climate and to promote adaptive capacities and the mitigation of climate change and work towards disaster risk reduction. Water is one of the key inputs for agricultural productivity and its timely and adequate supply is directly proportionate with the economic produce. As water is becoming a limiting factor for crop production, soil and water management should be the key to the development of eco-friendly and climate smart agriculture for both irrigated as well as rainfed areas. The precision water management using smart tools needs to be practiced in both the field crops and horticultural crops which are being grown diverse agro-ecosystems for sustaining the food production. We need to critically analyze the existing water resources of different agro-ecological regions, current crop water demand of and prioritization and wide scale adoption of eco-friendly climate resilient smart water management techniques and integrating them in to water management policy interventions or schemes such as Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) for ensuring water and food security.

Analysis of Water Resources Scenario in India

Owing to increasing demand of water for sectors like domestic, industrial and energy, there is a severe constraint in the availability of water for irrigation sector / farming. It has been assessed that the utilizable water is 1123 BCM (690 BCM from surface 433 BCM ground water) only, which accounts to about 28% of the water derived from precipitation. Annual groundwater recharge is about 433 BCM, of which 212.5 BCM is used for irrigation. Out of net sown area of about 141 Million ha, the net irrigated area in India as on 2013-14 is 77.9 Million ha (55% of net sown area). The remaining 63.1 Million ha area is under rainfed condition (45% of net sown area). Similarly, the gross irrigated area of the country is 120.4 Million ha accounting for 55% of the gross cropped area (219.2 M ha). At the same time, the availability of water for agriculture in India is expected to decline from 84% in 2010 to 74% by 2050. Even within agriculture, the water demand for different sub-sectors or farming systems will change significantly in the coming years. The enhanced water demand in domestic, industrial and energy sectors will need additional 222 BCM water by 2050. Low water use efficiency and poor maintenance of irrigation systems are some of the major problems while managing the water resources in the country. The field crops and horticultural crops have huge potential to earn foreign exchange revenue provide they are supported with advanced water management practices Hence, there is a strong need to focus on precision agriculture with special emphasis on eco-friendly climate resilient and smart water management tools for these crops.

Precision Agriculture and Precision Water Management

Precision agriculture plays vital role in enhancing the crop production significantly and it is emerging as a mainstream practice with the advent of recent developments in sensors, IoTs, Drone technology and big data analytics. In addition, the innovations in remote sensing at different platforms, geospatial sciences, robotics, Spatial decision support systems (SDSS), Variable rate technology (VRT), Digital Soil Mapping (DSM), Information and Communication Technologies (ICTs) have special advantage in terms of generating spatio-temporal data at required frequency and spatial scale for precision agriculture.

Similarly, as both surface and groundwater irrigation suffer from considerable losses leading to low water use efficiency, we need to give more emphasis to precision water management. It was reported by Performance Overview and Management Improvement Organization of Central Water Commission, Government of India that the utilization efficiencies for surface water and groundwater were assumed to be 50% and 70%, respectively (Brahmanand and Singh, 2022). At the same time, irrigation water demand (84% of total water demand in India) faces stiffest competition from industry and energy sectors and we have to judiciously use the existing water resources. The changing climate is expected to worsen the scenario further (Brahmanand *et al.,* 2013). Hence this necessitates us to promote precision water management using IoT tools in agricultural sector.

An automated irrigation system means the operation of the system without or with a bare minimum of human intervention. It ensures adequate quantity of irrigation water at critical crop growth stages to avoid water stress. This has further broadened the scope of precision irrigation water management by integrating the senor-based water management. The precision irrigation water management system utilizes the components like drip irrigation, GPS and GIS technologies, variable rate of irrigation and monitoring and automation (Prahraj *et al.,* 2017). Drip Irrigation is a sub category of micro-irrigation system which allows water to drip or trickle slowly drop by drop to the rhizosphere zone of plants either from above the soil surface or buried below the surface. It distributes water through a network of valves, pipes, tubing, and emitters. It supplies water directly into the root zone and hence minimizes the losses through evaporation, runoff and percolation (Das and Singh, 1989). Moreover, it aids in fertilizer use efficiency along with water use efficiency through practice of fertigation.

The components of precision irrigation system are depicted in Figure 1.

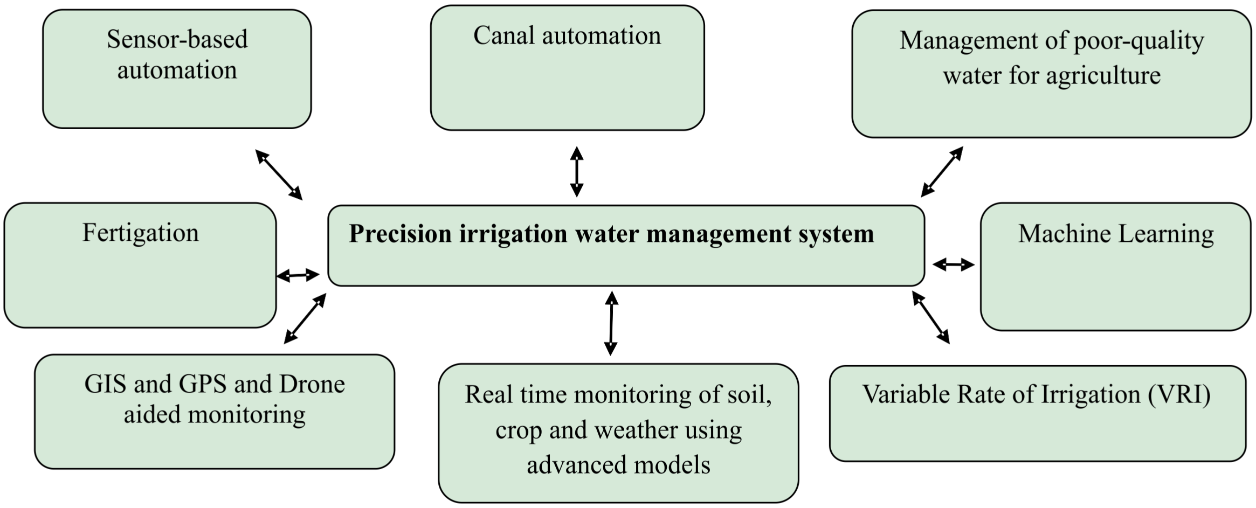


Figure 1. Components of Precision Irrigation Water Management system

IoT enabled precision irrigation will help in accurate monitoring of water level in both surface water resources like canals and groundwater resources like tube wells, automation in surface and micro irrigation systems, water quality monitoring and flood and drought assessment and management and crop insurance. For higher adoption of IoT enabled precision water management in India, we need to focus on cluster approach on basis of cooperative farming model, strengthening public-private partnership, better convergence with national flagship programmes, and wide scale promotion of mobile app based digital farming solutions. Overall, multi-pronged approach is essential for successful adoption of IoT enabled precision irrigation in farmers' fields.

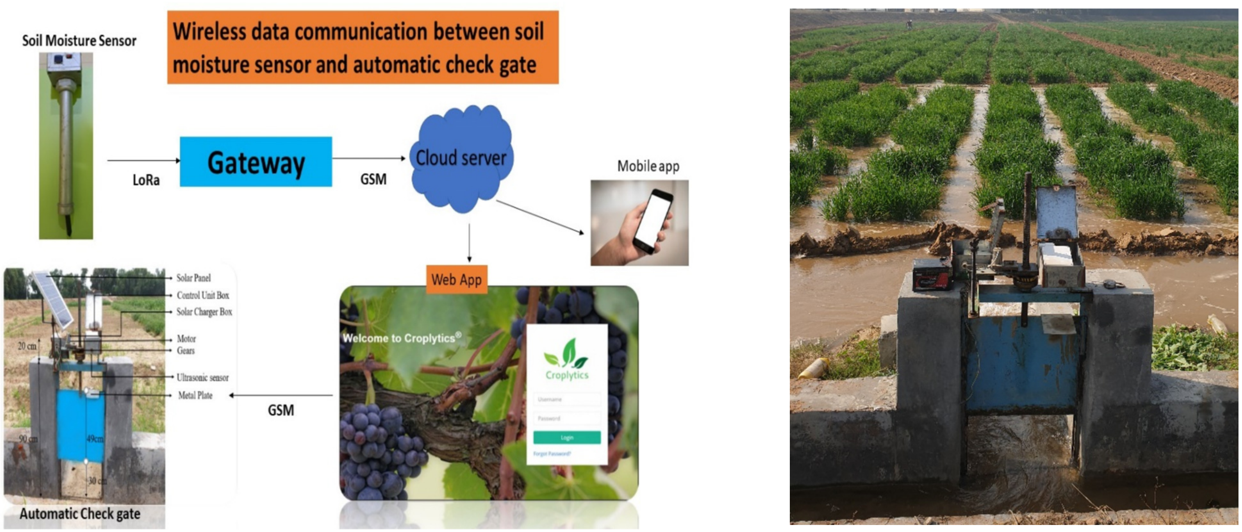
At global level, several nations initiated the research efforts on precision irrigation water management and succeeded to some extent in expanding the cultivated area under this efficient water management system. Advances made in precision irrigation systems at global level, in general, and Israel, in particular, give us a vivid idea about their diversified advantages. For example, the soil moisture sensor developed by Viridix helps in estimation of water potential available to roots of plants without any help of network or electricity. The measurement of stem water potential for design of optimum irrigation scheduling in orchard crops has been made quite convenient through miniature implanted sensors developed by Saturas. Similarly, gravity micro irrigation system developed by N-Drip makes use of field topography and gravity works well even with dirty water without use of filters thereby enhancing operational efficiency. As precision irrigation water management is in nascent stage in India, there is tremendous scope for its higher level of adoption in phase wise manner with full utilization of recent advances in machine learning, digital farming solutions etc. With the advent of new emerging techniques in the field of information technology both at international and national level, the automation and real time data monitoring under precision irrigation system will be further strengthened.

Some selected smart tools for sustainable water management interventions are described here.

Smart tools for sustainable water management

Solar-powered soil moisture sensor-based automatic surface irrigation system

Soil moisture sensor-based automatic surface irrigation system developed by Water Technology Centre, ICAR-Indian Agricultural Research Institute, New Delhi is breakthrough technology which enhances the water application efficiency of surface irrigation system. This system consists of an automatic check gate, soil moisture sensors, a communication system, and a web/mobile interface. The check gate is made of an aluminium sheet attached to an iron frame installed in the field inlet channel. The solar-powered capacitance soil moisture sensor installed in the field senses the real-time data and transmits it to the cloud server via the gateway. The wireless communication was established with LoRa and GSM modules. The cloud server is wirelessly connected to the check gate and mobile or web interface though GSM module. Farmers can download the mobile app from Google Play. The real-time soil moisture status can be monitored on mobile by the user/farmer and the system enables the farmers to start (open check gate) and off (close the check gate) the irrigation based on real-time soil moisture status from anywhere/remotely. The irrigation scheduling with an automatic real-time soil moisture-based system helped to save nearly 25% of water as compared to the conventional method of irrigation. It also helped to enhance water use efficiency and water productivity by 30% as compared to conventional practice. The automatic surface irrigation system has the potential to make a significant contribution in water, labor and energy saving in commercial crop cultivation.



Solar-powered soil moisture sensor-based automatic surface irrigation system

Automated ICAR-flexi rubber dams for watersheds

The installation of rubberdams in watersheds act as better drought resilience structure and it will significantly help in additional water storage, crop productivity and net economic returns to the

ICAR Flexi Rubber Checkdam

farmers. This technology has potential to create an additional water storage capacity of about 52,000 to 80,000m^3 for irrigating about 30-40 ha of paddy in kharif and 6 ha of pulses, oilseeds and vegetable crops / commercial crops in rabi season. It has potential to enhance the net returns of the farmers up to Rs.48,000/ha. The automated rubber dams will aid the farmers in operational convenience and optimum water storage and water use efficiency.

Drone-based Water Stress Monitoring

Huge scope exists for drone-based irrigation monitoring and identification of variable plant stress zones in India. The application of drones is more significant in identification of mechanical problems in canal operation and maintenance which may lead to sustainable water resource development. The prospects for use of drones in agricultural sector in India will be improved with the new regulations issued by Government of India. This will aid in enhancing water productivity of field crops and horticultural crops.

Design of tank cum well system in watersheds in rainfed areas

The tank cum well system technology along the drainage line in a watershed is recommended for plateau areas having slope of 2 to 5%). The site for the technology should be selected in such a way that the area should have a well-defined valley where the runoff flows either as overland flow or channel flow. The well is constructed about 100 to 300 m downstream of the tank to tap the water that is lost by seepage from the tank. A set of 15 tanks and wells is required for a catchment area of 500 ha to irrigate 60 ha area. The technology is well suited for both field crops horticultural species.

Conclusion

The vulnerability of different agro-ecosystems has been found to be on increasing trend due to the higher frequency and magnitude of extreme climatic risks or events in the recent years. This affects the productivity of field crops and horticultural crops. Hence, the efforts must be concentrated on evolving eco-friendly and climate resilient sustainable agricultural practices through best utilization of created water resources and adoption of innovative water management practices leading to higher water use efficiency and water productivity. The smart water management tools like automated irrigation and automated rubber dams will aid in sustainable water resource management thereby enhancing water productivity in agricultural sector and ensuring water and food security.

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Role of Crop Simulation Modelling in Transforming Indian Agriculture

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ABSTRACT

Crop simulation modelling plays a vital role in transforming Indian agriculture by addressing key challenges such as climate change, resource management, and sustainability. As an agrarian economy, India faces several hurdles, including erratic weather patterns, water scarcity, and soil degradation, all of which affect agricultural productivity and food security. This manuscript explores how crop simulation models can revolutionize Indian agriculture by providing data-driven insights and predictive capabilities. These models help farmers adapt to climate change by simulating crop responses to varying climatic conditions and enabling the adoption of climate-resilient practices, such as drought-tolerant crop varieties and adjusted sowing dates. Moreover, crop simulation supports precision agriculture by optimizing the use of water, fertilizers, and pesticides, leading to increased productivity and reduced environmental impact. By forecasting yields and identifying yield gaps, simulation models aid in improving risk management and decision-making for farmers. They also facilitate the adoption of sustainable farming practices, such as crop rotation and soil management, to enhance long-term productivity. At a broader level, crop simulation models assist policymakers and agricultural planners in formulating evidence-based policies to ensure food security and economic stability. Overall, crop simulation modeling serves as an essential tool in transforming Indian agriculture, enhancing productivity, sustainability, and resilience in the face of evolving environmental and socio-economic conditions. As technology advances and more data becomes available, these models will continue to play a crucial role in shaping the future of agriculture in India.

Key words: Simulation modeling, Impact assessment, Calibration and validation, Potential yield simulation, Climate change, Optimization

Introduction

India, with its vast and diverse agricultural landscape, plays a critical role in the global food supply, contributing significantly to the world's production of cereals, pulses, fruits, and vegetables. Despite the substantial agricultural base, Indian agriculture faces significant challenges, including the vagaries of weather, water scarcity, soil degradation, and inefficient agricultural practices. With the looming threat of climate change, which poses risks to crop productivity, the need for innovative, data-driven solutions to ensure food security and sustainable agriculture has never been more urgent. Crop simulation modelling has emerged as one such innovative approach, offering powerful tools for understanding crop growth, predicting yield, and formulating strategies for resource-efficient farming. These models integrate various environmental factors, including climate, soil, and crop management practices, to simulate crop behaviour over different time scales. By evaluating various scenarios, crop simulation models help predict the potential outcomes of different farming practices, leading to informed decision-making.

As India grapples with challenges such as water scarcity, soil fertility depletion, and the pressures of increasing food demand, crop simulation modelling has shown promise in addressing many of these issues. By simulating how crops respond to changing environmental conditions and management practices, these models provide valuable insights into optimizing inputs, improving productivity, and mitigating risks associated with climate variability. This manuscript explores the role of crop simulation modelling in transforming Indian agriculture, delving into its applications, challenges, and potential for contributing to the country's agricultural future. We will discuss key crop simulation models used in India, their applications across different regions and crops, and how these models can contribute to optimizing agricultural practices. Furthermore, we will examine the challenges faced in the implementation of crop modelling technologies and propose ways forward for overcoming these obstacles to realize their full potential.

Understanding Crop Simulation Modelling

Definition and Concept

Crop simulation modelling refers to the use of mathematical models to simulate the growth, development, and yield of crops under varying environmental conditions. These models integrate a wide range of factors such as climate, soil, crop genetics, and management practices to provide predictions about how crops behave in different scenarios. They are valuable tools for both research and practical applications in agriculture, offering insights into improving crop management, optimizing inputs, and mitigating risks related to pests, diseases, and climate variability.

Types of Crop Simulation Models

Crop simulation models can generally be classified into two categories:

Deterministic models: These models provide a single, fixed prediction for a given set of input conditions, without accounting for random variability. They are useful in steady-state conditions but may be less effective in environments where variability plays a significant role.

Stochastic models: In contrast to deterministic models, stochastic models incorporate randomness and variability in their predictions. This makes them more suitable for situations where environmental factors such as weather, pest outbreaks, and soil conditions can vary.

Components of Crop Models

Crop simulation models typically consist of several key components:

Climate data: Weather variables such as temperature, rainfall, solar radiation, and wind speed are essential for simulating crop growth and productivity. Accurate, high-quality weather data are critical for model accuracy.

Soil data: Soil properties, including texture, moisture content, nutrient levels, and pH, are fundamental inputs for simulating the availability of water and nutrients to the crops.

Crop management practices: These include planting dates, irrigation practices, fertilizer application, pest and disease management, and other agronomic factors that influence crop growth.

Crop growth algorithms: These algorithms simulate key physiological processes in crops, such as photosynthesis, transpiration, and biomass accumulation, and help predict the growth and development of crops over time.

Historical Context and Development of Crop Simulation Models

Early Developments in Crop Modelling

The concept of crop simulation modelling emerged in the mid-20th century as researchers and scientists sought ways to better understand and predict the impact of environmental factors on crop growth. Early crop models were relatively simple and focused on a few environmental variables, often relying on empirical relationships derived from field experiments. These early models were limited in scope but laid the foundation for the more sophisticated models that followed. One of the earliest developments was the CERES model (Crop Environment Resource Synthesis), developed in the 1970s. This model aimed to simulate the growth and yield of crops like maize, wheat, and rice by considering factors such as temperature, solar radiation, water availability, and soil properties. Ritchie (1972) was a key figure in developing the CERES model, which was initially designed for use in the United States but later adapted for different regions, including India.

Evolution and Advancements in Crop Simulation Models

By the 1980s and 1990s, the advent of more powerful computers and access to greater quantities of data led to the development of more sophisticated models that could simulate not only crop growth but also the effects of various management practices. DSSAT (Decision Support System for Agrotechnology Transfer), developed in the 1980s, became one of the most widely used crop simulation systems globally. DSSAT integrates various crop models to simulate the growth of multiple crops under different environmental and management conditions.

In India, crop simulation models began to gain prominence in the 1990s, driven by the country's urgent need to enhance crop productivity in the face of increasing population and environmental stress. Indian research institutions such as the Indian Agricultural Research Institute (IARI) and Indian Council of Agricultural Research (ICAR) played a significant role in adapting international models like CERES and DSSAT for Indian conditions. These models were calibrated using local data on weather patterns, soil types, and crop varieties to improve their accuracy in predicting crop performance under Indian conditions.

Key Crop Simulation Models Used in India

India uses several advanced crop simulation models, each with its unique features, designed to address specific agricultural needs across the country. Here are some of the key models:

CERES (Crop Environment Resource Synthesis)

Developed initially in the U.S. and later adapted globally, including India, CERES models simulate the growth of major crops like rice, maize, wheat, and sorghum under varying environmental and management conditions. CERES-Wheat, for example, can predict the yield of wheat by simulating its response to climatic factors such as temperature and rainfall, along with soil moisture and nutrient levels. The model uses data on crop phenology, growth stages, and water use to predict potential yield. In India, several researchers have extensively used the CERES-Wheat model to assess the impacts of different management practices on wheat yield, particularly in relation to irrigation and sowing dates. The model has been calibrated using local data, enhancing its accuracy in the Indian context.

DSSAT (Decision Support System for Agrotechnology Transfer)

DSSAT is one of the most comprehensive crop simulation systems globally and has found wide application in India. The model allows the simulation of multiple crops and can incorporate diverse environmental factors such as soil moisture, temperature, and nutrient availability. DSSAT has been used for crop yield prediction, pest and disease forecasting, and climate change impact assessment. In India, DSSAT has been adapted to local conditions through calibration for crops such as rice, maize, and pulses. Researchers use DSSAT to simulate how these crops respond to different weather patterns, helping to optimize sowing dates, irrigation practices, and fertilizer use.

APSIM (Agricultural Production Systems Simulator)

The APSIM model, developed in Australia, is another widely used crop simulation tool. APSIM simulates both crop growth and agricultural systems, including interactions between crops, soil, water, and nutrients. In India, APSIM has been used in studies assessing water use efficiency and soil-crop interactions, particularly in rain-fed areas where water scarcity is a significant issue.

INFOCROP

INFOCROP is a crop simulation model developed specifically for India, by ICAR-Indian Agricultural Research Institute (Aggarwal et al. (2006a&b)). It simulates the growth of major crops, including rice, wheat, and groundnut, by integrating weather data, soil conditions, and crop management practices. INFOCROP has been applied in various parts of India to assess the impacts of different irrigation and fertilization strategies on crop productivity. The model is highly relevant for Indian agriculture, as it can be used to test crop management strategies that optimize resource use.

CropSyst

The CropSyst model is another useful tool for simulating crop growth and productivity in India. It is particularly helpful in evaluating different cropping systems and their interactions with the environment. CropSyst has been used for various crops in India, including wheat, rice, and maize, to assess soil-water-nutrient interactions and help in better managing crop rotation practices.

Applications of Crop Simulation Models in Indian Agriculture

Crop simulation models have become invaluable tools for improving agricultural productivity and sustainability in India. These models help simulate the potential outcomes of various farming practices, offering farmers and policymakers insights that can guide decision-making in areas such as crop management, irrigation, and climate change adaptation. Below are some key applications of crop simulation models in Indian agriculture:

Climate Change Impact Assessment

One of the most critical applications of crop simulation models in India is their role in assessing the impacts of climate change on crop yields. India is highly vulnerable to the effects of climate change, including changes in rainfall patterns, temperature fluctuations, and the increased frequency of extreme weather events. Crop simulation models help estimate how these changes might affect crop growth and productivity, enabling farmers to adapt more effectively. Models like DSSAT and CERES-Wheat have been used to simulate the impact of varying temperature and rainfall patterns on major crops such as wheat, rice, and maize. Studies using these models have shown that slight increases in temperature could result in reduced yields, especially for heat-sensitive crops like wheat. Additionally, changes in precipitation patterns could affect water availability for irrigation, further influencing crop productivity. For instance, Subash and Ram Mohan (2012) used DSSAT to evaluate the impact of climatic trends and variability in rice-wheat system productivity over the Indo-Gangetic Plains of India. Subash *et al.*(2021) studied Integrated Assessment of Climate Change Impacts on Rice–Wheat Farms of IGP-India through Multi-Climate-Crop Model Approach at farm level.

Water Management and Irrigation Optimization

India faces significant challenges related to water scarcity, especially in regions dependent on irrigation for crop production. Crop simulation models are increasingly being used to assess and optimize irrigation practices, ensuring that water resources are used efficiently and sustainably. Models like INFOCROP and APSIM have been applied to evaluate the effects of different irrigation strategies on crop yields in water-limited regions (Sena *et al*. (2014), Subash *et al*. (2014) and Sudhir-Yadav *et al*. (2011a&b). By simulating soil moisture, evapotranspiration, and crop water demand, these models help in designing irrigation schedules that optimize water use while maintaining crop productivity. Additionally, crop models allow for the evaluation of rainwater harvesting strategies and the role of soil water retention in improving water use efficiency. Subash *et al.* (2015) used APSIM to capture the effectiveness of irrigation management decisions in rice-based cropping sequence in the Upper-Gangetic Plains of India and it was found that a rice irrigation regime of 5 days AWD may be recognized as the good irrigation management schedule for rice with a moderate yield penalty.

Crop Management and Fertilizer Optimization

Crop simulation models are also used to optimize nutrient management in Indian agriculture, where excessive and imbalanced fertilizer use is a common challenge. By simulating the relationship between soil nutrient availability, crop growth, and yield, these models can recommend appropriate fertilizer application rates and timing to improve crop productivity while minimizing environmental impacts. APSIM and DSSAT have been widely used to evaluate the effectiveness of different fertilization strategies in various crops. These models simulate nutrient dynamics in the soil and predict crop responses to varying fertilizer doses. For example, Balwinder-Singh *et al*. (2015a&b) used APSIM to evaluated different options for increasing the productivity of the rice-wheat system of north-west India while reducing groundwater depletion. The effects of mulch and irrigation management on wheat in Punjab India also evaluated using APSIM Model (Balwinder-Singh *et al.*, (2011)). Gaydon *et al*. (2017) evaluated use of in addressed different management options with APSIM Model in cropping systems of Asia.

Pest and Disease Forecasting

Pests and diseases are major constraints to crop production in India, and their management is crucial for maintaining food security. Crop simulation models can be used to simulate pest and disease dynamics under different weather conditions, enabling farmers to forecast outbreaks and take preventive measures. Models like CropSyst and APSIM have been used to simulate the relationship between weather conditions and the development of pests and diseases. These models can predict the likelihood of pest infestations based on environmental factors such as temperature, humidity, and rainfall, helping farmers make timely decisions on pesticide applications and integrated pest management (IPM) practices.

Yield Prediction and Crop Insurance

Crop simulation models are also used for yield prediction, which plays a crucial role in agricultural planning and policy. Accurate yield prediction is essential for crop insurance schemes, which help farmers mitigate the risks associated with crop failures. Crop models like CERES-Wheat, INFOCROP, and DSSAT can simulate crop yield under varying weather conditions, input management, and agronomic practices. These predictions are essential for designing crop insurance products and pricing policies that reflect the actual risks faced by farmers.

Precision Agriculture and Site-Specific Management

The use of precision agriculture techniques in India has been growing, and crop simulation models are central to these efforts. By integrating data from remote sensing, geographic information systems (GIS), and field sensors, these models can provide site-specific recommendations for crop management, irrigation, and fertilization. In regions with diverse agro-ecological conditions, crop models like APSIM and DSSAT can simulate spatial variability in crop growth, helping farmers tailor their practices to specific field conditions. This approach leads to more efficient resource use, higher yields, and reduced environmental impact.

Breeding for Climate-Resilient Varieties

Crop simulation models are also instrumental in the development of climate-resilient crop varieties. By simulating the performance of different crop genotypes under varying environmental conditions, these models can help identify varieties that are more resistant to heat stress, drought, and disease. CERES and DSSAT models have been used to simulate the performance of different wheat, rice, and maize varieties in response to climate variability. These simulations assist breeders in selecting genotypes that have higher yield potentials under changing climatic conditions.

Challenges and Limitations of Crop Simulation Models in India

While crop simulation models have proven to be useful tools in improving agricultural practices and decision-making in India, there are several challenges and limitations associated with their widespread application. These challenges range from data availability and model calibration to the lack of trained personnel for model implementation. Understanding these limitations is crucial for improving the use of crop models and overcoming barriers to their adoption.

Data Availability and Quality: One of the most significant challenges in using crop simulation models in India is the lack of high-quality, consistent, and long-term data. Accurate input data, including weather variables, soil properties, and crop management practices, is essential for calibrating and validating crop models. In India, however, many regions lack reliable weather data, soil data, and crop-specific management information. Weather data from meteorological stations is often sparse, especially in rural and remote areas, where a majority of farming takes place. In many instances, the data available may be incomplete, outdated, or recorded at infrequent intervals, which makes it difficult to use them effectively in crop models. Furthermore, soil data, including information on soil texture, organic matter content, and nutrient levels, is often not available at the desired scale or level of detail.

Moreover, crop management practices such as sowing dates, irrigation practices, and fertilizer applications are highly variable across regions and farms. The lack of comprehensive and standardized data on these practices hampers the effectiveness of crop simulation models, as these models rely on accurate input data to generate reliable predictions. To address these data gaps, remote sensing technologies and modern data collection methods (such as drones, sensors, and satellite imagery) can be leveraged. Integrating these technologies with crop simulation models can provide more accurate and real-time data, enabling better predictions and more precise agricultural recommendations.

Model Calibration and Validation: Model calibration and validation are essential steps in ensuring that crop simulation models provide reliable predictions. However, this process can be time-consuming and challenging, particularly in India's diverse agro-climatic conditions. The large number of factors influencing crop growth, such as soil variability, micro-climates, and changing agricultural practices, makes model calibration and validation a complex task. In India, crop models like DSSAT, CERES, and APSIM have often been calibrated using data from specific regions, which may not be representative of all agro-ecological zones in the country. The lack of regional calibration and validation studies is a limitation, as it means that crop models may not always be accurate for different locations and crop varieties.

Calibration and validation studies should be extended to more regions and agro-climatic zones of India, especially under changing climatic conditions. Local agricultural experiments, field observations, and farmer participatory trials can be used to collect data for better model calibration. Collaboration between research institutions, universities, and government agencies can help overcome this limitation and improve the accuracy of crop models.

Complexity of Model Structures: Crop simulation models are complex and require a high level of expertise to operate effectively. These models integrate various physical, biological, and chemical processes, such as photosynthesis, water and nutrient dynamics, and pest management, into a single system. Understanding and interpreting the results generated by these models requires specialized knowledge in agricultural science, meteorology, and computer programming. In India, there is a shortage of professionals with the technical expertise required to operate these models, especially in rural areas. Farmers, extension workers, and even researchers may not have the required training to use crop simulation models effectively. Capacity building is crucial to improving the understanding and use of crop simulation models. Training programs for farmers, extension officers, and researchers can help bridge the knowledge gap. Universities, agricultural research institutions, and government agencies should take the lead in providing these training programs to ensure that crop models are used to their full potential.

Limited Awareness and Acceptance among Farmers: Despite the proven benefits of crop simulation models, there is limited awareness and acceptance of these tools among Indian farmers. Many farmers are not familiar with the concept of crop simulation, and there may be skepticism regarding the reliability and applicability of model-based recommendations. Traditional farming practices are deeply rooted in rural communities, and farmers may be hesitant to adopt new technologies unless they can see immediate, tangible benefits. Moreover, the complexity of crop simulation models may deter farmers from using them, as they may perceive these tools as too technical or difficult to implement in their day-to-day farming practices. To promote the adoption of crop simulation models, awareness campaigns should be launched at the grassroots level. These campaigns can demonstrate how crop models can help optimize yields, reduce resource use, and improve resilience to climate change. In addition, extension services can play a vital role in translating the outputs of crop models into practical, actionable advice for farmers. These outputs should be communicated in simple, user-friendly formats, such as mobile apps, SMS services, and advisory notes.

Integration with Other Agricultural Technologies: Another challenge in using crop simulation models in India is the lack of integration with other agricultural technologies. In many instances, crop models are used in isolation without integrating them into broader farm management systems or decision support platforms. This lack of integration limits the potential of crop models to provide comprehensive solutions for farmers. Farm management involves a range of activities, including irrigation scheduling, pest and disease management, fertilizer application, and harvest planning. Crop simulation models need to be integrated with other technologies such as Geographic Information Systems (GIS), remote sensing, and decision support systems to provide a holistic approach to farm management. To overcome this challenge, there is a need for the development of integrated platforms that combine crop simulation models with other agricultural technologies. These platforms can provide farmers with real-time data on weather, soil moisture, pest infestations, and crop growth, enabling them to make informed decisions based on a comprehensive view of their farm operations.

High Computational Requirements: Crop simulation models, especially those that simulate complex interactions between crops, soil, and the environment, require substantial computational resources. High-performance computing is needed to run these models effectively, especially when simulating large areas or long-term scenarios. In India, the availability of such computing resources is limited, especially in rural and remote areas. To address this issue, cloud computing platforms can be used to host crop simulation models. Cloud computing can provide farmers and researchers with access to powerful computational resources without the need for expensive infrastructure. Additionally, mobile-based platforms can be developed to run simplified versions of crop models, making them more accessible to farmers with limited technical expertise.

Policy and Institutional Support: Although crop simulation models have demonstrated their potential in improving agricultural productivity and sustainability, there is a lack of policy and institutional support for their widespread adoption in India. The integration of crop simulation models into national agricultural policies and programs is still limited, and there is a lack of coordination between different stakeholders involved in agriculture. Governments at both the national and state levels should provide more support for the development and application of crop simulation models. This can include funding for research, infrastructure development, and capacity-building initiatives. Additionally, policies that promote the use of precision agriculture and data-driven decision-making should be encouraged.

How Simulation Modeling Can Transform Indian Agriculture in the Future

Simulation modeling has the potential to play a pivotal role in transforming Indian agriculture, driving it toward increased sustainability, efficiency, and resilience in the face of climate change and evolving socio-economic conditions. As India's agricultural sector grapples with numerous challenges—such as erratic weather patterns, declining soil health, and water scarcity—simulation modeling offers an innovative solution to address these issues, providing farmers, researchers, and policymakers with valuable insights to make informed decisions. Here's how simulation modeling can transform Indian agriculture in the future:

1. Climate Change Adaptation

India is particularly vulnerable to climate change, with shifting rainfall patterns, increased frequency of extreme weather events, and rising temperatures impacting crop yields and farming systems. Simulation models, by incorporating climate scenarios and future projections, can help predict the impacts of climate change on crop growth, water availability, and pest dynamics. This enables farmers to adopt climate-resilient practices, optimize irrigation schedules, and select crop varieties that are best suited to changing climatic conditions. Crop models can help farmers adapt to and mitigate the risks posed by climate change, ensuring stable and reliable yields.

2. Precision Agriculture

The future of farming in India lies in precision agriculture, where technology is used to optimize every aspect of farm management. Simulation models are at the heart of precision farming systems, which rely on real-time data from weather stations, soil sensors, and satellite imagery. These models can simulate field conditions, predict crop performance, and provide recommendations for optimal input use (e.g., water, fertilizers, pesticides). By integrating crop simulation with technologies like remote sensing and Geographic Information Systems (GIS), farmers can make better decisions, reduce input waste, and increase productivity. Precision agriculture will empower farmers to farm more efficiently, leading to higher productivity and reduced environmental impact.

3. Improved Resource Management

India's agriculture is highly dependent on resource management, particularly water and soil health. Simulation models can optimize irrigation schedules, reducing water consumption in regions facing water scarcity. By simulating soil moisture levels and crop water requirements, models can guide farmers on when and how much water to apply, conserving water resources. Similarly, crop models can simulate nutrient dynamics and soil health, helping farmers manage fertilizer use and avoid overuse, which can lead to soil degradation and water pollution. Effective resource management, guided by simulation models, will contribute to sustainable agricultural practices and environmental conservation.

4. Pest and Disease Forecasting

Pests and diseases are major constraints to agricultural productivity in India. The use of crop simulation models integrated with pest and disease forecasting models can provide early warning systems for farmers. By simulating the interactions between weather conditions, pest cycles, and crop growth, these models can predict pest outbreaks and recommend preventive measures. This will not only reduce the reliance on chemical pesticides but also minimize the losses due to pest infestations, leading to healthier crops and reduced environmental pollution.

5. Decision Support for Policy and Planning

At a macro level, simulation modeling can assist policymakers and agricultural planners in formulating better policies. By simulating different policy scenarios—such as changes in subsidy structures, water management practices, or crop diversification strategies—decision-makers can evaluate the potential impacts before implementing them. This will enable evidence-based policymaking that aligns with the diverse needs of Indian agriculture, fostering sustainable development and improving food security.

6. Enhancing Productivity and Reducing Yield Gaps

India's agricultural productivity lags behind many other countries due to gaps between potential yields and actual yields. Simulation models can help identify these yield gaps by simulating ideal growing conditions for crops and comparing them with current farm-level practices. This information can guide farmers toward adopting best practices for crop management, such as appropriate planting dates, crop rotation, and pest management strategies. By reducing yield gaps, simulation models will play a crucial role in increasing agricultural productivity and ensuring food security in India.

7. Empowering Farmers with Knowledge

Simulation models can also serve as an educational tool for farmers. Interactive platforms and mobile apps based on crop simulation models can provide farmers with tailored advice on when to plant, irrigate, fertilize, and harvest their crops. With proper training, farmers can use these tools to make data-driven decisions, reducing reliance on guesswork and traditional practices. This empowers farmers to improve their farming practices, increase efficiency, and enhance their income prospects.

8. Facilitating Climate-Smart Agriculture

The future of Indian agriculture lies in adopting climate-smart agricultural practices that enhance productivity, reduce emissions, and increase resilience to climate change. Simulation models provide the foundation for climate-smart agriculture by helping farmers evaluate different climate-resilient practices, such as the use of drought-tolerant crops, agroforestry, and organic farming. Models can also evaluate the carbon footprint of various farming practices, enabling farmers to choose environmentally friendly options that contribute to climate change mitigation.

Simulation modeling holds immense potential to revolutionize Indian agriculture in the coming decades. By enabling climate change adaptation, promoting precision agriculture, optimizing resource management, forecasting pest and disease outbreaks, and empowering farmers with knowledge, simulation models will become indispensable tools in Indian farming. For this transformation to materialize, collaboration between researchers, extension services, technology developers, and policymakers is crucial. With continued advancements in simulation technology and increased access to data, India can build a resilient, sustainable, and productive agricultural sector that meets the growing food demands of its population.

Conclusion and Future Directions

Crop simulation models have great potential to transform Indian agriculture by providing valuable insights into crop management, water use, climate change impacts, and other critical factors. However, there are several challenges that need to be addressed to maximize the benefits of these models. By improving data availability, model calibration, training, and integration with other technologies, India can leverage crop simulation models to enhance agricultural productivity, sustainability, and resilience. Future research should focus on improving the accuracy of crop models under diverse agro-ecological conditions, developing user-friendly tools for farmers, and integrating crop simulation models into broader agricultural decision-making frameworks. Collaboration between government agencies, research institutions, and private sector players will be crucial to ensuring that crop simulation models can play a transformative role in Indian agriculture.

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Nitrogen in Cereal Systems: Challenges in Constructing an Accurate N Budget

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Introduction

Nitrogen (N) is crucial for the biosphere, with 99% existing as inert N_2 in the atmosphere. Annually, approximately 425 Tg of reactive nitrogen (N_R) is produced through natural processes and human activities, including 120 Tg from the Haber-Bosch process (IFA, 2016) and 30-51 Tg from biological N fixation (BNF) (Ladha and Chakraborty, 2016). Despite the essential role of N_R in crop production and human nutrition, many regions still face N deficits that threaten food security (Ciceri and Allanore, 2019). With a projected global population of 9.7 billion by mid-century, fertilizer demand is expected to rise significantly (FAO, 2018; Rivas and Nonhebel, 2017).

Effective N management is key to global food security and minimizing environmental impact. Fertilizer N has contributed to a 20% increase in atmospheric N_2O since the industrial revolution (Park *et al.*, 2012), with N emissions now surpassing CO_2 emissions. Nitrogen budgeting therefore plays a crucial role in reducing the dependence on synthetic fertilizer N in agriculture, which is essential for ensuring long-term food security and environmental sustainability. Accurate N budgeting optimizes nutrient management, reducing excessive fertilizer use and N leakage to the environment, while improving crop N use efficiency (NUE). Understanding the role of organic and non-synthetic N sources enables farmers to adopt sustainable practices, promoting healthy soil, higher yields, and minimizing environmental impacts from over-reliance on synthetic fertilizers.

N Budget in Agriculture

Over 50 years ago, Allison (1955) noted the challenges in constructing accurate N budgets, describing it as an ‘enigma’. Greenland and Watanabe (1982) identified three key difficulties: (1) measuring changes in total N content, (2) quantifying N fixed by biological fixation (BNF), and (3) accounting for N losses. Since then, significant progress has been made in these areas, leading to more accurate N budget estimates for arable crops (Liu *et al.*, 2010; Smil, 1999; Zhang *et al.*, 2015) and major cereals (Ladha *et al.*, 2011). While synthetic N input and crop harvest output are relatively well-estimated, uncertainties remain in other N flow measurements. Despite varying methodologies, trends across studies are generally consistent.

Globally, synthetic N fulfills about 50-57% of the total N needs for croplands and grazing pastures (Table 1). The remaining 43-50% comes from biological fixation (BNF) (~43-44%) and other sources such as deposition, manure, and crop residues (Ladha *et al.*, 2020). Regarding N removal, crop harvests account for 36-42% of total N output, while losses represent 57-64%. A global N budget for

Table 1. Global N inputs and outputs (Tg yr^{-1})

Nitrogen flows	Smil (1999) Year mid-1990s All crops	Liu *et al*. (2010) Year 2000 All crops	Zhang *et al*. (2015) Year 2010 All crops	Ladha *et al*. (2011) Year 2010 Maize, rice and wheat
Inputs	169	137	174	94
Synthetic N	78	68	100	58
Biological N fixation	33	22		11
Manure N	18	17		14
Residue N	14	11		6
Deposition	20	14		5
Sedimentation	4	3		
Seed	2	-		
Output	165	148	174	
Crop harvest	85	81	74	49
N leaching	17	23	100	49
N gaseous	33	20		
N erosion	20	24		
Loss from crop canopy	10	-		
Change in soil N	4	-13	0	-1

Obtained from Ladha *et al*. (2020)

maize, rice, and wheat created by Ladha *et al*. (2016) revealed that 50% of the 100 Tg of synthetic N applied worldwide is used for growing these three key cereals. This N budget was derived from global data on N sources and sinks over a 50-year period (1961-2010), during which 1,551 Tg of N was harvested from these crops. Of this, 48% came from fertilizer N, while the rest was supplied through soil depletion or non-fertilizer sources such as manure and atmospheric deposition. Non-symbiotic BNF, primarily from free-living bacteria and cyanobacteria, was the largest contributor, supplying 25% of the total N in the crops (Fig. 1). Additional contributions came from manure (14%) and atmospheric deposition (6%), while crop residues and seeds made minor contributions.

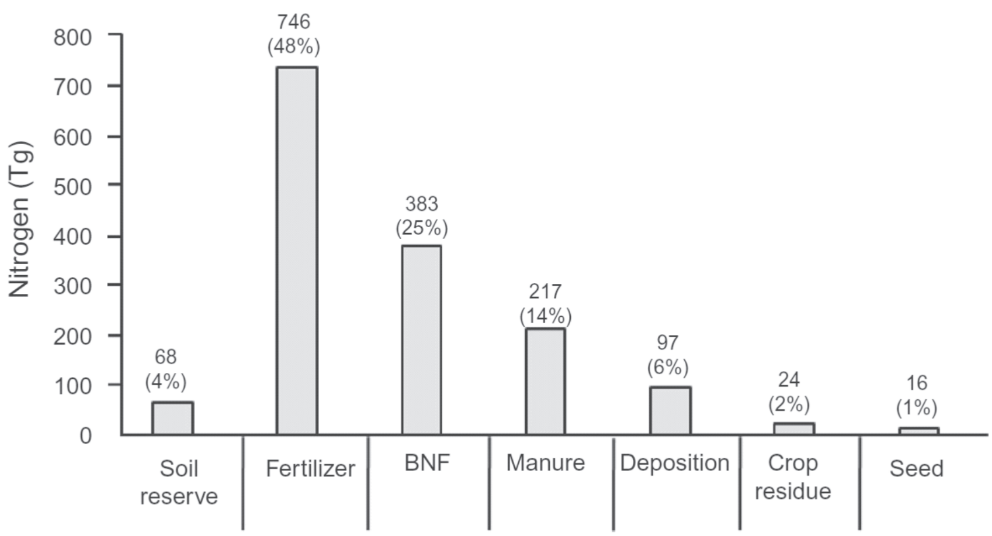

Figure 1. Sources of N in major cereal crops (maize, rice, and wheat) [Values are global total (Tg) for 50 years (1961–2010); Source: Ladha *et al*. (2020)

These results underscore the need to consider all N sources, including synthetic fertilizers, manure, residues, deposition, symbiotic and non-symbiotic BNF, and indigenous soil organic nitrogen (SON), when developing strategies to enhance the NUE.

Soil N Supply: A Crucial Component Often Overlooked

Soil organic matter (SOM) is a key indicator of soil fertility, serving as an energy source for heterotrophs and a vital reservoir of plant nutrients, especially N in the form of soil organic nitrogen (SON), which accounts for 90-98% of total soil N. However, agricultural practices and the use of synthetic N fertilizers can impact SON levels. While N fertilizers may increase SON, they can also lead to their accelerated loss. It is essential to assess whether long-term use of synthetic fertilizers results in a decline in SON. An ecosystem-based approach to nutrient management is recommended to sustain and enhance both organic and mineral nutrient reserves over time.

A study by Ladha *et al.* (2011) analyzed data from 135 studies across 114 cereal-based long-term experiments at 100 global sites, spanning decades and varying land-management and climate conditions. The analysis included 580 observations of soil N from control (unfertilized or zero-N) and synthetic N-fertilized treatments. The study assessed changes in total soil N under continuous cultivation and fertilization. Soil N declined by 11% under zero-N conditions, but only by 4% when synthetic N was applied. The findings also showed that long-term use of synthetic fertilizers resulted in a slower decline in SON compared to no fertilizer use. On average, SON was 10% higher with synthetic N compared to zero N, though it still declined over time with or without synthetic N application. The study highlighted that synthetic N fertilizer enhances crop growth, which in turn increases carbon and nitrogen inputs into the soil, driving higher SOM or SON levels. These results align with Powlson *et al.* (2010), who concluded that long-term synthetic fertilizer use slows the decline of SOM and may even increase it compared to zero fertilizer input.

Globally, several studies have estimated changes in soil nitrogen (N) due to continuous cultivation and N fertilization. Smil (1999) estimated a global N accumulation of 4 Tg in arable soils during the mid-1990s, while Liu *et al.* (2010) reported a negative soil N balance of 11.53 Tg (~11 kg N ha-1 yr-1) in 2000. However, significant regional variability in soil N changes (either depletion or accumulation) has been observed, as highlighted by Liu *et al.* (2010) (Fig. 2). A meta-analysis of global long-term experiments found a negative N balance of 32 Tg for maize and 62 Tg for wheat over a 50-year period (1960-2010). Conversely, a positive N-balance of 26 Tg was observed for rice during the same period (Ladha *et al.*, 2016). Annual variations in soil N in N-balance studies were

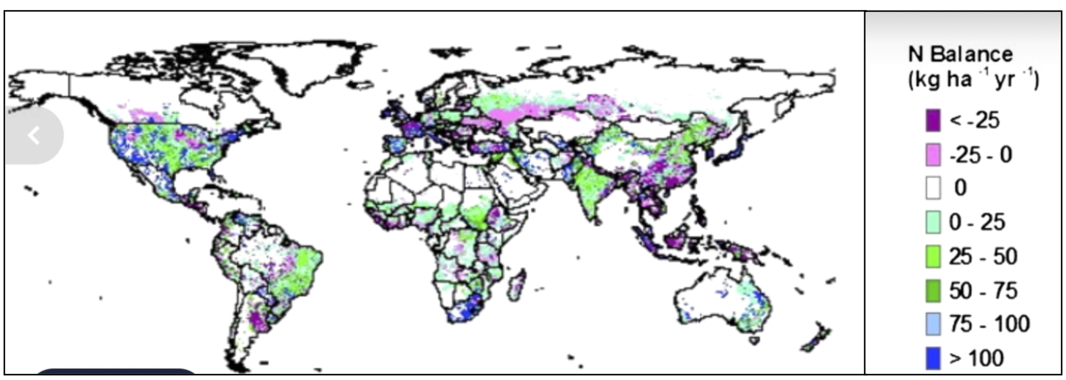

Figure 2. Global map of soil N balance in cropland (Liu *et al.*, 2020)

generally small, suggesting that major cereal production systems are close to steady state or N-equilibrium.

N Recovery Efficiencies and Surplus N

The global average NUE for cereals is 0.55, based on the N-difference method, and 0.50 using the 15N-dilution method. These values align with other reported NUE estimates for food crops, which range from 0.43 to 0.59 (Smil, 1999; Sheldrick *et al*., 2002; Liu *et al*., 2010; Howarth *et al*., 2002; Janzen *et al*., 2003). Global studies on maize, rice, and wheat agroecosystems reveal NUE values ranging from 0.20 to 0.90 (Ladha *et al*., 2005). The average N recovery efficiency (REN) was found to be 7% lower when calculated using the 15N-dilution method (0.50) compared to the N-difference method (0.55). Additionally, it was estimated that 6.5% of applied N remains residual N for subsequent crops over five growing seasons. A significant variation in REN values exists between researcher-managed trials and farmers' fields, often due to economic limitations and sub-optimal crop management practices. On-farm assessments have reported REN estimates of 0.31 kg N per kg of fertilizer N applied, which is 25% lower than the average REN of 0.41 observed in research-managed plots (Dobermann *et al*., 2004).

Ladha *et al*. (2016) estimated that the N surplus from fertilizer use in maize, rice, and wheat crops amounted to 848 Tg over a 50-year period (1961-2010), with surpluses of 7.7 Tg, 10.0 Tg, and 9.8 Tg, respectively, in 2010 alone. The average annual N surplus rates for these crops in 1990 were 1.37 kg ha^{-1} for maize, 1.72 kg ha^{-1} for rice, and 1.0 kg ha^{-1} for wheat. However, these rates decreased over the following two decades, with values of 0.5, 1.0, and 0.9 kg ha^{-1} $year^{-1}$, respectively. This decline may be attributed to improved N management practices, leading to better NUE in crops. Zhang *et al*. (2015) reported global NUE averages of 0.46 for maize, 0.38 for rice, and 0.43 for wheat. Their estimates of N surplus were 15 Tg, 18 Tg, and 17 Tg per year for maize, rice, and wheat, respectively, based on the total nitrogen inputs (from all sources) and outputs (N removed in harvested crop biomass).

Legacy Effect of N Fertilization

Legacy soil N refers to the residual N remaining in soils from past agricultural practices, natural processes, or environmental changes. This effect has limited relevance in short-term N budgeting studies. As illustrated in Fig. 3, the yield response curve from field trials under fertilizer N treatments shows that yield at the control plot tends to decrease over time (the red point on the vertical dashed line of NF_N, N from non-synthetic fertilizer sources, moves downward). This decline is mainly due to the diminishing legacy effect of previous N inputs before the control plot was established (Quan *et al*., 2021). The "legacy effect" of N fertilization creates discrepancies between nitrogen use efficiency (NUE) calculated using the N-balance approach (harvested N divided by all N inputs) and the N-difference approach (harvested N in fertilized plots minus harvested N in non-fertilized control plots, then divided by N fertilizer inputs). This difference is attributed to the residual impact of N fertilization from previous seasons. Fertilizer N not only meets plant N needs for the current growing season but also replenishes soil N, supporting long-term N supply. Except for newly established croplands, most farms have a history of fertilizer or manure use, indicating the widespread legacy or replenishment effect of fertilizer application. This suggests that NUE assessments should consider a long-term perspective. The N-balance approach assumes a quasi-steady-state of soil N stocks and accounts for long-term legacy effects, but it may overestimate or underestimate the actual NUE if

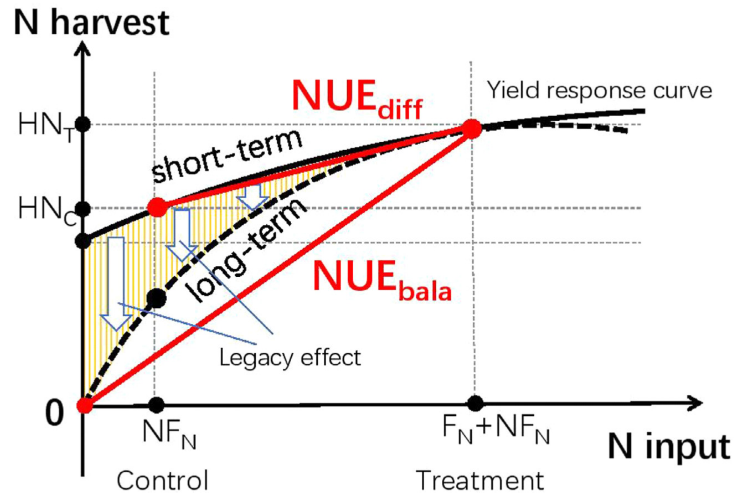

Figure 3. Fertilizer N legacy effect [HN_T and HN_C are harvested N in fertilizer and control plots, respectively; F_N and NF_N are fertilizer N-inputs and non-fertilizer N inputs, respectively; NUE diff and NUE bala are two approaches (see text for details)] (Quan *et al.*, 2021)

significant soil N mining or accumulation occurs during the observation period. A recent study revealed that non-fertilizer N sources consistently contributed more to crop N uptake than synthetic fertilizer sources, especially in rice, which had the highest fraction of non-synthetic nitrogen at 57% (Chakraborty *et al.*, 2024; In preparation). The legacy effect of fertilizer N was most evident in rice, indicating a significant carryover of N from previous seasons. The legacy effect, represented by the difference between REN_T (taking all N input N sources) input) and REN_S (only fertilizer N as input), which reflects the carryover of fertilizer N from prior seasons, was highest in rice at 21%, followed by maize at 16%, and wheat at 14%.

Conclusions

Nitrogen budgeting remains a challenging task due to the complexity of accounting for all the input and output components involved in calculating the N balance. While fertilizers are a primary source of nitrogen for crops, significant contributions from other sources, such as biological nitrogen fixation, manure, crop residues, and atmospheric deposition, must also be considered. Relying solely on fertilizer N inputs for budgeting would overlook these vital contributions and lead to inaccurate estimates. Although the European Union has proposed a simplified framework for nitrogen budgeting, it does not provide a comprehensive solution for accurately estimating all input parameters. This highlights the need for more robust and inclusive methodologies that account for the full spectrum of N sources and sinks in agricultural systems.

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Agrometeorology: Its Applications in Crop Yield Estimation and Enhanced Disease and Pest Management

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ABSTRACT

Current and forecasted weather information is instrumental in planning crop schedules and organizing farm operations, including the application of sprays, to optimize yields and returns. Additionally, it offers early warnings about potential pest and disease outbreaks, enabling timely implementation of effective plant protection measures to mitigate damage before it occurs. Methods such as remote sensing and crop modeling are widely used to predict yields and forecast pest and disease outbreaks. Crop simulation models rely on environmental and management conditions but require future data projections for accurate forecasts. Forecasting methodologies combine diverse datasets, including meteorological data, farmer observations, agrometeorological indices, and remote sensing, either independently or synergistically. Remote sensing, by detecting changes in the spectral properties of crop canopies caused by biotic stress, offers a precise and objective alternative to traditional visual evaluation methods, enhancing the accuracy and speed of stress assessment. So, this article highlights how agrometeorology plays a critical role in estimating crop yield and managing diseases and pests.

Introduction

Agricultural meteorology is a scientific discipline focused on examining the interactions between meteorological conditions and agricultural production processes. It studies how natural weather elements—such as light, temperature, moisture, atmospheric pressure, and carbon dioxide levels—impact crop growth, animal health, pest and disease dynamics, and overall agricultural productivity. This field encompasses all stages of agriculture, from seeding and growth management to harvesting and storage. The primary objective of agrometeorology is to understand the spatial and temporal patterns of these environmental factors and provide a scientific foundation for agricultural zoning, crop planning, microclimate management, weather forecasting, and advisory services. By applying this knowledge, agrometeorologists support farmers in optimizing the use of climatic resources, adopting precision agriculture practices, mitigating the effects of climate change, and minimizing risks from adverse weather. These efforts aim to boost crop yields, lower production costs, and promote the economic and environmental sustainability of agriculture. Agrometeorology enables the prediction of pest and disease outbreaks, offering farmers timely and scientifically informed recommendations for their prevention and control. For instance, conditions such as elevated temperatures and high humidity often favor the proliferation and dissemination of specific pests and pathogens. By utilizing weather forecasts, farmers can implement targeted control strategies in advance. This proactive approach not only minimizes crop losses but also enhances the economic efficiency of agricultural production.

With increasing population and food demand, it has become extremely necessary to estimate the increase in yield needed to fulfil the needs of future generations. Based on the weather, soil and crop data crop models provide a scientific and reliable estimate for this purpose. Crop modeling in agriculture utilizes quantitative data on ecophysiological processes to predict plant growth and development in response to environmental conditions and crop management practices. These models simulate a crop's response (such as growth or yield) to environmental factors, management practices, water, weather, and soil conditions, as they interact throughout the growing season. They replicate the growth and development of crops to mathematically represent the various components of the cropping system. The origins of crop modeling trace back to the 1960s, when researchers combined physical and biological principles to model agricultural systems. Agricultural models depend on measurable inputs (collected through sensors, machines, or manual methods) to estimate outputs of interest, such as plant growth, crop yield, soil nitrogen, or crop development stages. Not only crop yield estimation but increasing in yield in a sustainable manner is also necessary to feed the increasing population in future. To minimize the infestation losses and t0 protect our crop from excessive use of pesticides and insecticides, it is necessary to predict the damage in the earlier stages. Remote sensing techniques are valuable tools for detecting crop stresses, including nutrient deficiencies, pest infestations, disease progression, and drought conditions. These methods enhance both spatial and temporal resolution compared to conventional pest monitoring approaches (Datta *et al.,* 2008). Remote sensing of plant diseases and pests functions as a "radiodiagnostic" tool for plants, enabling efficient, non-invasive, and spatially extensive monitoring of biotic stresses. Research in this field began as early as the 1980s, with Riley (1989) demonstrating the potential of identifying areas affected by plant diseases and pests through the visual interpretation of aerial and satellite imagery. Subsequently, Nilsson (1995) elaborated on various applications of remote sensing and image analysis in plant pathology. The integration of advanced computer science and sensing technologies has facilitated the utilization of diverse remote sensing data for detecting plant diseases and pests.

Over the past few decades, substantial advancements have been achieved in the development of sensing systems, feature extraction methodologies, and algorithms across multiple spatial and temporal scales, unveiling innovative prospects for the remote monitoring, early detection, and effective management of plant health and pest dynamics.

Various Techniques for Estimating Crop Yields

Crop yield is the ratio of agricultural input to output and represents the amount of yield produced per unit area of cultivated land. It is commonly used as a measure of agricultural productivity. Various factors, including production practices, pests, pathogens, environmental changes, and consumer demand, can influence crop yield. Therefore, monitoring crop yield is crucial for the agricultural and economic development of any country. It helps inform decisions related to imports and exports, pricing, crop distribution, and future planting strategies. Researchers have developed various methods to track and predict crop yield, including vegetation indices and statistical models.

Crop yield estimation goes beyond forecasting production; it plays a vital role in enhancing profitability, promoting sustainability, and ensuring food security. Accurate yield predictions provide farmers with insights into potential harvest outcomes, enabling better management decisions, efficient resource utilization, and increased profitability. Additionally, yield estimation supports global food security by predicting food availability and informing policy-making. Crop yield estimation can be done through crop models and it relies on simulating crop growth and development using mathematical equations. These models are capable of predicting biomass and grain yield while analyzing the interactions between plants, soil, and the atmosphere. Despite their utility, crop models are often constrained by spatial variability and the extensive calibration required for accurate results. Other than crop modelling remote sensing techniques offer significant potential for estimation of crop yield. Remote sensing data has become an essential resource for estimating crop yields. Satellites such as MODIS (Moderate Resolution Imaging Spectroradiometer) capture imagery of crops from space, offering critical insights into crop health, growth stages, and yield potential. Vegetation indices derived from this data play a key role in evaluating crop conditions. For example, the Normalized Difference Vegetation Index (NDVI) quantifies vegetation greenness, which is closely linked to biomass and, consequently, yield predictions. Satellite data is particularly advantageous for large-scale crop yield assessments, enabling the monitoring of extensive areas that would be infeasible to survey manually. This approach is especially effective for tracking field crops like wheat, maize, and soybeans, providing vital information throughout the growing season.

Pre-harvest crop yield prediction is crucial for preventing potential crises and enabling decision-makers to implement reliable strategies for ensuring food security. Remote sensing offers significant advantages in crop monitoring and yield prediction by capturing variations in soil, climate, and biophysical or biochemical changes. Techniques such as multispectral and hyperspectral imaging, as well as radar and lidar, are widely utilized for these purposes. Satellite data with high spatial resolution remains one of the most effective methods for crop monitoring and assessing crop parameters. Field or laboratory devices for evaluating crop spectroscopic parameters can accurately identify and quantify various biochemical and biophysical attributes of crops. Additionally, these devices can serve as early indicators of plant infections. However, their applicability is limited for monitoring crops over large areas (Ali *et al.*, 2022). Crop growth monitoring and yield estimation based on remote sensing data rely on identifying parameters, analyzing statistical relationships, and constructing estimation models. While simple and widely used, remote sensing reflects only surface-level physical conditions, lacks explanatory mechanisms, and faces limitations in temporal and spatial coverage due to satellite revisit cycles and weather conditions. Reflection from plant cover is influenced by various factors, including the radiation characteristics of individual plant components such as leaves, root systems, soil, moisture, canopy structures, spatial patterns, angular distribution of incoming radiation, and sensor direction. Additionally, factors like soil radiation scattering, biomass concentration, plant assimilation state, and photosynthetic efficiency play a role. Vegetation reflectance can be categorized into four types, each with specific functions: (a) reflectance from individual plant parts (such as pigments in single organs), (b) reflectance from plant canopies, (c) reflectance indicating plant presence and health, and (d) reflectance related to canopy structure and texture (Usha and Singh, 2013). Conversely, crop growth models, grounded in biophysical laws and driven by factors like light, temperature, moisture, and fertilization, provide a systematic and quantitative representation of key physiological processes such as photosynthesis, respiration, and transpiration, offering a deeper understanding of crop growth and yield formation (Ma *et al.*, 2022). However, both techniques have their own limitations. Vegetation indices using spectral data can be constrained by context-specific factors, as growth rate variations across different orchard types can lead to inaccurate large-scale production estimates. One solution is to focus on species-specific periods to assess the growth status of fruit trees, which can provide more accurate data. For methods that rely on computational modeling, the accuracy of predictions depends on stable trends in historical data to forecast future yields. However, unexpected changes in climate, soil, irrigation, or cultivation practices can complicate this process. The interactive effects of environmental conditions and shifts in field management practices can further undermine model accuracy. To overcome these challenges, He *et al*. (2022) recommended combining different inference algorithms to improve the fit of models to variable data. The selection of the prediction method is crucial for optimizing crop yield accuracy. Large-scale production methods may benefit from data obtained through remote sensing technology, while smaller-scale operations might rely more on vegetation indices derived from samples collected via tractors, sub-sampled areas, or smartphones. Each method can be refined over time by integrating diverse data types and utilizing automated tools, improving both reliability and cost-effectiveness.

Utilizing Remote Sensing for Pest and Disease Forecasting in Agriculture

Crop diseases and pests have long posed significant challenges in agriculture. Traditional monitoring methods are often time-consuming and inefficient. However, advancements in remote sensing, meteorology and plant growth monitoring technologies have enabled the use of multi-source data to monitor crop diseases and pests, marking a new trend and breakthrough in agricultural development. The occurrence of crop diseases and pests, such as the reproduction and transmission of bacterial spores and the emergence of insect eggs, is a prolonged process influenced by landscape patterns and habitat conditions (Zhang *et al.*, 2019). By combining multi-source temporal remote sensing data with habitat information, it is possible to enhance the monitoring and early warning systems for rice diseases and pests. Pest and disease forecasting plays a crucial role in agriculture by helping farmers reduce crop losses, minimize environmental impact, save money, make informed decisions, and improve crop health. Early warnings of potential disease outbreaks enable farmers to take preventative measures, thus reducing crop losses. By limiting the need for excessive pesticides and chemicals, forecasting promotes sustainable farming practices. Moreover, it offers a cost-effective approach by optimizing input use, such as fertilizers and pesticides, and informing decisions about crop selection and rotation. Additionally, disease forecasting contributes to better crop health by allowing timely interventions. Pest forecasting, which involves analyzing data from biology, mathematics, and statistics, predicts pest outbreaks using various methods. These methods include field surveys, which provide detailed pest information but are labor-intensive, sticky boards and Wi-Fi cameras for pest monitoring, white screens with specific light sources to trap certain insects, and remote sensing technology, which offers valuable data on pest incidence, potential damage, and outbreak risks.

When crops are affected by pests and diseases, their physiological and biochemical parameters, such as pigment content, water, protein levels, and structural characteristics, are altered, resulting in visible symptoms like blotches or shriveling. These changes are reflected in the crop's spectral reflectance, which forms the basis for remote sensing monitoring of vegetation diseases. Remote sensing detects these changes, as pests and diseases modify the crop's cellular structure, pigments, water, nitrogen content, and leaf shape, causing shifts in reflectance spectra. For example, disease-induced changes lead to a reduction in the green region, an increase in the red region, and a decrease in the near-infrared region. The near-infrared reflectance of diseased crops is significantly lower than that of healthy crops, often due to reduced biomass from leaf damage. Remote sensing, by capturing these spectral changes, provides a valuable tool for detecting and identifying plant diseases (Zheng *et al.*, 2023). Multi-spectral remote sensing technology captures vegetation features by obtaining spectral information across different wavelength ranges. It is effective for large-scale, real-time monitoring of pests and diseases, offering low-cost and rapid response capabilities. However, its lower spectral resolution may not meet all specific needs. For example, rice diseases often show weak or delayed spectral responses in the early stages of stress, particularly in complex field environments. As a result, accurately detecting early rice diseases can be challenging using this technology for pest and disease monitoring (Qin *et al.*, 2023).

Hyperspectral remote sensing data from low-altitude flights, with high spectral and spatial resolution, is highly effective in detecting diseases in green vegetation. Multi-temporal remote sensing data is valuable for mapping crop diseases on a regional scale. Spectral classification methods, such as the NDVI spectral profile, show significant differences between healthy and diseased crops, indicating crop stress. Remote sensing technology can greatly enhance the spatial accuracy of disease diagnostics, making agriculture more sustainable and reducing the need for costly pesticide use. To fully harness these advanced technologies, a multi-disciplinary approach involving plant pathology, engineering, and informatics is necessary. Collaboration across disciplines will improve decision support systems and increase the adoption of these techniques (Gogoi *et al.*, 2018).

Enhancing Agricultural Practices Through the Use of Agro Advisories

Agrometeorological advisory services assist farmers in making informed decisions regarding water and fertilizer management, pest and disease control, sowing and harvesting schedules and other farm practices. These services include weather forecasting, ranging from short-term nowcasting to long-term seasonal predictions. When combined with monitoring farm conditions, they provide practical farming advice to stakeholders across the agrifood system. The Food and Agriculture Organization (FAO) and the World Meteorological Organization (WMO) collaborate to enhance the capacity of their members to offer meteorological and related services to agricultural communities, thereby supporting the development of sustainable and economically viable agricultural systems. A key finding from the WMO's State of Climate Services report highlighted the importance of addressing the "last mile" barrier in agrometeorological advisory services. These services depend on data availability, quality, and the capacity of information producers. For advisories to positively impact livelihoods and improve food security, context-specific information must reach end users, such as farmers, in a timely manner, in the appropriate language, and with actionable guidance, often facilitated by mobile technologies. FAO's Global Outlook on Climate Services in Agriculture report underscores the investment gap in climate services for small-scale and marginalized farmers, emphasizing the need to ensure equitable communication of actionable information. Both FAO and WMO are developing projects to ensure that agrometeorological advisory services effectively engage vulnerable agricultural communities. (https://wmo.int/media/update/empowering-farmers-role-of-agrometeorological-services-sustainable-agriculture#:~:text=Agrometeorological%20advisory%20services%20help%20farmers,and%20other%20on%2Dfarm%20practices.). They also play a crucial role in helping farmers increase their yields by providing valuable information on weather conditions that impact agricultural practices. These advisories include weather forecasts, offering insights into rainfall, temperature, and wind speeds, enabling farmers to plan the timing for sowing, harvesting, irrigation and the application of fertilizers and pesticides. By optimizing the use of inputs, agro advisories allow farmers to apply resources more judiciously and efficiently, thereby reducing production costs. Additionally, season-specific advice is provided, with pre-season advisories suggesting the best practices based on forecasted conditions, such as recommending drought-tolerant crops in seasons with below-normal rainfall. As a result, farmers who utilize agro advisories often experience increased yields, reduced production costs, and ultimately higher net returns.

Conclusion

In an increasingly dynamic world, accurately forecasting crop yields is essential for developing effective agricultural strategies and ensuring food security. Crop yield influences food productivity and is crucial for maintaining food safety and availability, impacting everyone from policymakers to farmers and consumers. Thus, predicting crop yields provides valuable insights for guiding management and financial decisions. For increasing yield and minimizing losses proper pest and disease management is essential. Various techniques like remote sensing play a crucial role in this as it aids in the detection, forecasting, and management of pests and plant diseases, as well as monitoring crop quality throughout the growing season. It can detect early signs of pest infestation, such as color changes in the canopy or shifts in crop reflectance patterns, like identifying mite infestations in cotton fields using multi-spectral systems. It also helps forecast pest outbreaks and movements, allowing for targeted control measures that reduce pesticide use and minimize environmental impact. Additionally, it monitors crop health, facilitating timely interventions to improve yields. By combining remote sensing with machine learning, more accurate and timely interventions can be made. Apart from remote sensing agro advisories are assisting farmers for their better crop management in real time. Agro advisory services are a boon for the farming community, enhancing their knowledge of innovative farming practices, including the latest technologies and effective management strategies for both crop cultivation and animal husbandry. These services provide weather forecast-based agro-advisories, helping farmers select suitable crops and varieties in real-time. By adopting the recommendations from agro-meteorological advisories, farmers can make informed decisions about daily farm operations, reducing input costs and maximizing their benefits.

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- The Government of Goa established the Goa State Research Foundation (GSRF) through Act 8 of 2022 on 17th October 2022.
- The Foundation's primary focus (through its 23 objects and 33 functions) is promoting RESEARCH in the State of Goa at various levels across disciplines.
- Goa is the first and only state in India to have established a separate organisation (dedicated to promoting research at all levels across the disciplines in the state) through legislative assent and separate budgetary allocation.
- Establishing GSRF is a vital part of implementing the National Education Policy 2020.

Within a short period of its establishment, GSRF is promoting research through the following schemes:

- GSRF Doctoral Research Fellowship Scheme
- GSRF Post-Doctoral Fellowship Scheme
- GSRF Research Start-Up Grant Scheme
- GSRF Minor Grant Research Scheme
- GSRF Major Research Grant Scheme
- GSRF Summer/Winter School Scheme
- GSRF Interdisciplinary Research Interventions Scheme for Local Development (IRIS-LD).

In association with the Directorate of Higher Education (DHE) and the Goa State Higher Education Council, it conducted several programmes to reach out to the stakeholders:

- GSRF awareness and Stakeholders meeting (30 visits to colleges and Goa University)
- Faculty Development Programme on 'Enhancing Final Year Student Projects'
- Workshop on "Research Grant

In addition, the following special workshops/training programmes were conducted:

- Field Workshop for the Second Year B.Sc. Biology Students of Govt. College, Quepem
- State-level Workshop on "Understanding Research Methods – MLA 9th Edition" (In association with Vidya Prabodhini College, Porvorim.
- Managing Dissertations at the PG level (multiple colleges and Goa University)
- Academic Writing Workshop for Faculty Members (multiple colleges)
- A half-a-day brainstorming workshop for trainer resource persons to train High school and High Secondary School Students and Teachers in "Demystifying Research and taking research to the doorsteps of schools."
- Follow-up FDP programme on 'Enhancing Final Year Student Projects'
- IRIS-LD Interactive meeting with interested prospective applicants.
- Brainstorming workshop on forest-related research in association with the forest department, Government of Goa.

Periodic workshops, training programmes and talks to promote research are planned.

Government of Goa
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Establishes an Ambitious Plan by Doubling the Farmers Income for making Goa self – sufficient in milk, meat and eggs, also overcomes unemployment apart from making our State nutritionally vibrant.

Mukyamantri Sudharit Kamdhenu Scheme: Subsidy @90% is given to all categories of farmers for the purpose from 1 to 10 milch animals. Infrastructure Component at the rate of 80% for a unit of 10 animals with maximum subsidy of Rs. 2,59,200/- can be availed on application for purchase of Kamdhenu animals.

Revised Scheme for Incentive to Milk producers: 40% Composite Subsidy is paid on proceeds of milk poured by farmers to Dairy Co-op Societies/Bachat Gats which are registered with the department of A.H. & V.S. Rs.37,79,16,661/- is paid to milk producers in the State, during the year 2023-24, thus encouraging more farmers to take up Dairy business due to remunerative price for milk.

Pashupalan Scheme: Scheme to rear calf from birth to 27 months. Upto Rs.52,800/- per calf subsidy is provided for SC/ST and Dhangar Farmers and Rs.39600/- for General Farmers.

Community Dairy Farming Scheme(Amended 2021): Under this programme a group of minimum 5 persons as well as Self Help Groups, Farmers Club will be allowed to do farming under one roof with modern dairy farming concept with minimum 50 milch animals and maximum 200 milch animals, maximum subsidy upto Rs.1.75 Crore is provided to the group.

Varah Palan: The Beneficiary is eligible to purchase 6-22 (piglets) & 4-22 adult pigs @ Rs.120/- per kg body weight with proportionate subsidy @74% for female and 62.5% for male. For gobar gas, maximum unit cost Rs.50,000/- with maximum subsidy Rs.37,500/- and for piggery equipment maximum permissible cost Rs.34,800/- with maximum subsidy is Rs.26,100/-. For Shed construction Rs.2,000/- per piglet.

Goatery Scheme: Subsidy @75 % for purchase of 10 female & 1 male goat maximum subsidy of Rs. 50,625/-. 75%subsidy towards shed construction for Maximum Rs 22,725/-. Feeding cost for one year at 75% subsidy Rs. 58,719/- and transport cost of Rs. 5,000/- (outside State) & 2000/- (within state).

Dairy Equipment: Various Dairy Equipments like Milking Machine, Generator Set, Shed Washer, Ceiling Fans etc are provided under the Scheme with 75% subsidy upto Rs. 3.0 lakh subsidy per farmer.

THE GOA SMALL ANIMAL RESCUE MANAGEMENT SCHEME 2014(Amended): Grant in Aid Scheme has been introduced by the Department through local bodies to facilitate bringing out control and to curb Stray Dog population on public roads, beaches and other public places

THE GOA STRAY CATTLE MANAGEMENT SCHEME 2013(Amended): Grant in Aid Scheme introduced by Department to facilitate local bodies for impounding and management of Stray Cattle through Animal Welfare Organization / Gaushalas.




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