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Special Issue on

6th International Agronomy Congress (IAC-2025): Re-envisioning Agronomy for Smart Agri-food Systems and Environmental Stewardship

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6th International Agronomy Congress (IAC-2025)

The 6th International Agronomy Congress (IAC-2025) on *"Re-envisioning Agronomy for Smart Agri-food Systems and Environmental Stewardship"* will be held at CSIR-National Physical Laboratory, New Delhi, India, bringing together global experts, researchers, policymakers, industry partners, and young professionals. The Congress is jointly organized by the Indian Society of Agronomy in collaboration with the Indian Council of Agricultural Research (ICAR), ICAR-Indian Agricultural Research Institute (IARI), National Academy of Agricultural Sciences (NAAS), and the Trust for Advancement of Agricultural Sciences (TAAS). The event will feature a rich scientific programme including plenary lectures by world-renowned scientists, invited lead lectures across symposia, oral and poster presentations, sponsor sessions, and a curated exhibition. Delegates will also contribute extended summaries, which will be published in the Pre-Congress Proceedings, along with special publications developed for the event.

The Congress scientific themes span around ten priority areas, including climate-resilient agriculture, nature-based solutions, precision input management, genetic improvement, digital and energy-efficient mechanization, stress management, policy interfaces, agronomic education, and a dedicated conclave for young scientists and students. Together, these themes aim to highlight innovations, foster collaboration, and chart a forward-looking roadmap for sustainable, smart agri-food systems.

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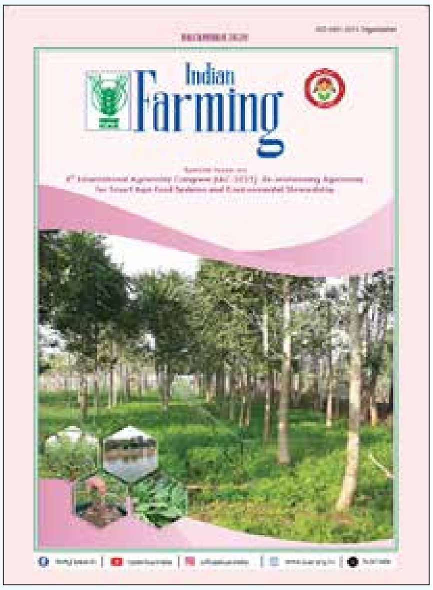

Cover I: IAC-2025

Cover IV: Integration and technological advancements in agronomy

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In This Issue

Presidential Message

AGRICULTURE continues to be the cornerstone of food, nutrition, and livelihood security, yet it faces unprecedented pressures from climate variability, soil and water degradation, declining factor productivity, and the need to balance production with environmental stewardship. In this evolving scenario, agronomy stands at the heart of the transformation, offering pathways to integrate science, technology, and indigenous knowledge into sustainable and smart agri-food systems. By aligning productivity gains with ecological resilience, agronomy can ensure that India meets the twin goals of food and nutritional security while contributing to global climate commitments.

It is in this context that the Indian Society of Agronomy, in collaboration with the Indian Council of Agricultural Research (ICAR), ICAR–IARI, National Academy of Agricultural Sciences (NAAS), and the Trust for Advancement of Agricultural Sciences (TAAS), is organizing the 6th International Agronomy Congress (IAC-2025) from 24–26 November 2025 at CSIR-National Physical Laboratory, New Delhi on the theme "Re-envisioning Agronomy for Smart Agri-food Systems and Environmental Stewardship." This event will provide a unique platform for scientists, policymakers, extension specialists, corporates, civil society, and young professionals from across the globe to deliberate on agronomic innovations and chart a roadmap for resilient and inclusive agricultural growth.

The technical programme of the Congress will address critical issues such as climate-resilient agriculture for carbon and land degradation neutrality, innovative approaches to manage biotic and abiotic stresses, gender empowerment and livelihood diversification, corporate and policy interfaces in food systems, and new vistas in agronomic education for Agriculture 5.0 and Viksit Bharat. A special conclave for young scientists and students will further provide opportunities to nurture ideas and build leadership for the future of agronomy.

The deliberations of this Congress are expected to generate actionable strategies that link cutting-edge science with farmer-centric practices, strengthen agronomic education and policy frameworks, and align with the Sustainable Development Goals (SDGs). The outcomes will not only enrich the discipline of agronomy but also reinforce its central role in ensuring sustainable food and nutrition security for India and beyond.

On behalf of the Indian Society of Agronomy, I warmly invite all members of the agronomic fraternity and allied stakeholders to participate in this landmark event and contribute to shaping the agronomy of tomorrow. Together, let us reaffirm our collective commitment to advancing agronomy for the benefit of farmers, society, and the environment.

KSharma

(S. K. Sharma)
President, ISA

Nurturing the Planet through Smart Agronomy

INDIA, with only 2% of global land, 4% of freshwater, and 11% of arable land, supports 17% of the world's people and 12.80% of livestock, placing immense pressure on natural resources and calling for re-envisioned management in agriculture. In recent decades, agriculture has witnessed unprecedented transitions driven by technological advancements, digital tools, and a growing consciousness of ecological sustainability. As we move towards the mid-21st century, the demand for food, feed, fibre, and fuel is projected to increase substantially, while the natural resource base continues to shrink. In this scenario, agronomy stands at the forefront, bridging science and practice, and integrating technologies, systems, and management principles to ensure resilience, productivity, and environmental harmony. The 6th International Agronomy Congress on "Re-envisioning Agronomy for Smart Agri-food Systems and Environmental Stewardship" provides a timely platform to deliberate upon the evolving paradigms of agronomic research and innovation in the face of complex agricultural and climatic challenges.

The theme of this congress highlights two vital dimensions: Smart agri-food systems and environmental stewardship. Smart agronomy, underpinned by precision agriculture, digital farming, sensors, remote sensing, and AI-driven analytics, has opened new avenues for optimizing resource use efficiency and decision-making at the field scale. Concurrently, environmental stewardship demands that agronomists take a holistic approach, emphasizing conservation agriculture, soil health restoration, carbon sequestration, and ecosystem services as integral components of sustainable intensification. At the Division of Agronomy, ICAR-IARI, our research, education, and outreach efforts are directed towards developing resource-efficient, climate-resilient, and sustainable crop production systems. Our focus has evolved from yield maximization to system optimization, ensuring that productivity gains are achieved with minimal environmental trade-offs. Long-term experiments, system-based research, and integration of novel technologies such as sensor-based nutrient management, water-smart practices, and carbon budgeting are guiding our strategic priorities.

This special issue of Indian Farming commemorating the 6th International Agronomy Congress reflects the collective vision, commitment, and scientific excellence of the agronomy community. It brings together thought-provoking perspectives, success stories, and innovations from across the globe that collectively demonstrate how agronomy can lead the transformation towards smart, sustainable, and climate-resilient agri-food systems. As agronomists, our responsibility extends beyond increasing production, it involves nurturing the planet's natural capital and empowering farmers through science-based, inclusive, and adaptive management solutions. The future of agronomy lies in collaboration, among disciplines, institutions, and nations, to address shared challenges and co-create knowledge for the global good. I extend my warm greetings to all contributors, participants, and readers of this special issue. I also extend my gratitude to Dr. G. Ravindra Chary and Dr. Arjun Singh in compiling the articles for this issue. May this collective endeavour inspire new ideas, partnerships, and innovations that reinforce agronomy's vital role in achieving food security, environmental sustainability, and societal well-being. Let us continue to re-envision agronomy, scientifically, sustainably, and smartly for the prosperity of people and the planet.

(Sanjay Singh Rathore)

Indian Farming 75 (12): 04-08; December 2025

Climate resilient agriculture for environmental sustainability

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Climate change poses a significant challenge to agriculture and food production, as it leads to extreme weather conditions, elevated temperatures and unpredictable rainfall, all of which adversely affect crops, soil and water resources. In India, the impact of climate change is anticipated to be particularly severe, especially in the northern regions, with increased heat and uncertain rainfall during the kharif season. To address these challenges, it is imperative to adopt sustainable farming practices that maintain soil health, prevent erosion and sequester carbon. Climate-resilient agriculture (CRA) is crucial for preserving environmental health and achieving the 2030 sustainability goals. To enhance the resilience of agriculture to climate change, it is essential to implement targeted nutrient management, organic farming, conservation agriculture, crop diversification and water-efficient farming practices. However, there are challenges in implementing these methods, even with governmental support. To promote the widespread adoption of CRA in India, a comprehensive long-term strategy and a multifaceted approach is required. Disseminating knowledge on adaptation and mitigation strategies is vital for broader acceptance. A robust CRA framework can contribute to the attainment of sustainable development goals, many of which emphasise climate change, agriculture, natural resources, and food security.

Keywords: Agro-biodiversity, Climate change, Climate resilient agriculture, Digital tools, Soil health improvement, Watersmart farming

CLIMATE change represents a significant challenge in contemporary society, primarily driven by greenhouse gas emissions from human activities. The sectors of agriculture and food production are particularly vulnerable to the impacts of climate change, which in turn affects food and water security. The increasing difficulty in food production necessitates the development of innovative adaptations to maintain sustainability in order to meet the demand of growing population. Extreme weather events such as heavy rainfall, floods, droughts and heatwaves adversely impact crops, soil and water resources. These climatic changes disproportionately affect rural areas, where many small-scale farmers depend on rainfall for their agricultural activities. It is projected that staple food yields could decline by up to 30% due to crop failures and reduced productivity. To ensure food, nutrition and environmental security, it is imperative to enhance food production while minimizing carbon and energy inputs. According to Indian Meteorological Department (IMD) 2022 report, temperature in certain regions of India exceeded normal levels by 3–8°C. Approximately 70% of India was affected by heatwaves, which led to reduced crop yields and water stress. Climate change is anticipated to have a profound impact on Indian agriculture. The minimum temperature is expected to rise more significantly than the maximum temperature, with the northern regions likely to experience greater heat than the southern regions. Rainfall during *kharif* season is expected to become unpredictable and temperature is projected to rise following the rainy season. These changes in seasonal patterns, temperature and precipitation can lead to challenges such as drought, floods resulting in substantial losses in yield. These effects will vary depending upon region, crop type, soil conditions, and farming practices. However, global warming is likely to diminish both the quality and quantity of crops. This is attributed to shorter growing periods due to high temperatures, increased prevalence of weeds and pests, reduced soil fertility and heightened soil erosion from erratic rainfall. Prolonged dry spells at the beginning, middle and end of the growing season can adversely affect crop production. A delayed onset of the monsoon followed by an extended dry period can result in early season drought. Insufficient soil moisture between rainfall events can lead to mid-season drought, while late season drought occurs when the monsoon concludes prematurely.

Promoting sustainable agriculture is crucial for addressing climate change within the agricultural sector. This involves implementing practices to maintain soil health, reduce erosion and enhance carbon sequestration. Climate resilient agriculture is essential for maintaining environmental sustainability in the face of climate change. Integrating traditional knowledge with modern scientific advancements facilitates development of localised strategies for climate resilience. Climate resilient agriculture should prioritise long term sustainability contributing to the achievement of 2030 sustainability agenda, which encompasses climate change, natural resource conservation and food security. With its adaptation and mitigation strategies, climate resilient agriculture is vital for sustainable development. To effectively address climate change, it is imperative to utilise crops that can withstand diverse weather conditions and to refine farming practices tailored to specific regions. Important adaptation measures include cultivating robust stress tolerant crop varieties, employing soil conservation farming techniques, managing nutrients based on specific regional needs and utilising advanced irrigation methods such as micro irrigation. Some of the key approaches to enhance the resilience of agriculture to climate change are discussed below.

Soil health improvement

Site specific nutrient management: Excessive application of fertilizers, such as nitrogen and phosphorus, to enhance crop yield has resulted in water pollution and degradation of terrestrial and coastal ecosystems, subsequently diminishing biodiversity. While nutrients are essential for global sustenance, it is crucial to apply fertilizers judiciously to promote crop growth and ensure sustainable agricultural practices. Ensuring application of balanced fertilizers is crucial for enhancing crop yields and maintaining agricultural sustainability. Nitrogen is among the essential nutrients needed for soil fertility. Nitrogen is a vital nutrient for enhancing crop growth; however, only less than 30% of the applied N has been utilised effectively. Inefficient fertilizer use and suboptimal water management are primary contributors to reduced crop productivity. The production and application of N fertilizers are energy-intensive processes that contribute to carbon emissions. Integrated Nutrient Management (INM) offers a viable solution to these adversaries. INM enhances soil nutrient and water retention, carbon sequestration and nutrient utilisation efficiency.

Organic farming: Organic farming represents a sustainable approach to land management. This approach can mitigate environmental impacts and enable farms to better adapt to climate change compared to conventional farming. It reduces greenhouse gas (GHG) emissions, enhances farm biodiversity, maintains soil health and bolsters food security and farmer autonomy. Although organic farming yields are lower than those of conventional farming, it remains a sustainable option. Organic products can fetch higher prices, thereby improving the profit margin, albeit with low productivity due to higher market prices. The focus of organic farming on maintaining soil fertility and health contributes to climate change adaptation. It employs closed nutrient loops, minimises losses from runoff and evaporation and avoids synthetic fertilizers. Consequently, organic farming exhibits higher soil organic carbon than conventional farming. They also support greater species diversity and cultivation of local varieties, enhancing resilience to extreme weather conditions. It also demonstrates superior water retention with 15–20% improvement in groundwater recharge, rendering organic farms drought resistant.

Conservation agriculture: Conservation Agriculture (CA) is implemented on 3.5 Mha in India. The key practices within CA encompass zero tillage, raised bed planting, direct seeded rice, utilization of crop residues and crop diversification. CA represents a sustainable approach to farming that can maintain or enhance crop yield, profitability and environmental health. CA contributes to improved soil quality, facilitates water filtration, retain soil moisture and reduces soil erosion and runoff. Reduced run off results in fewer nutrients, such as nitrate and phosphorus, being washed away from fields into water bodies thereby mitigating issues like water pollution. In conventional farming, there is a higher risk of nitrate leaching into groundwater. It is an integral component of climate smart agriculture as it enables quicker planting, minimise the soil disturbance and reduces fossil fuel consumption. Compared to conventional farming, CA sequester more carbon in the soil, support greater soil biodiversity and emit fewer GHGs making it a climate friendly practice.

Agro-biodiversity

Resilient crop varieties: The development of stress-tolerant crops is essential for addressing weather changes and supporting farmers. The improved varieties of crops that withstand adverse conditions such as drought, extreme temperatures, and floods have been developed through National Agricultural Research System in India. The development of these varieties is crucial for maintaining and enhancing crop production in the face of climate change. A crop's stress tolerance indicated its ability to grow and yield effectively even under adverse conditions. Under the National Innovations in Climate Resilient Agriculture (NICRA) programme of ICAR, high-yielding and stress-tolerant varieties of wheat and maize have been developed that can endure heat and drought stress. In Uttar Pradesh, adoption of flood tolerant rice variety BinaDhan 11 has enhanced income by ₹ 10,890/ha.

Crop diversification: Cereal based cropping systems are resource intensive and contribute significantly to greenhouse gas emissions, carbon and energy footprints and groundwater pollution. The inclusion of legume crops diminishes the requirement of N fertilizers. Legumes exhibit a smaller carbon and water footprint compared to cereals due to their lower GHG emissions. Legumes also contribute nitrogen to the soil potentially reducing global CO_2 emissions. In the Indo-Gangetic Plains, conventional rice-wheat cropping system is a

Conservation agriculture practice in maize

In situ soil moisture conservation in maize

significant source of GHG and exhibits higher global warming potential due to increased methane emission. Consequently, it is imperative to transition these systems especially the rice-wheat system to alternatives that are more carbon and energy efficient productive and environmentally sustainable. The implementation of direct seeding for rice and zero tillage for wheat along with the addition of crop residues substantially reduced GHG emissions which demonstrated that global warming potential can be decreased by 44–47% by transitioning from traditional systems of tilled wheat and transplanted rice to zero till wheat and direct seeded rice or zero tillage wheat with rice residue and direct seeded rice without compromising productivity. Additionally, inclusion of millets enhances energy productivity, system productivity and economic efficiency in the diverse agricultural zones of eastern India. Integrating millets or legumes into cereal based systems can reduce C foot print of crops by 32–315%.

Integrated farming system: To ensure food security while addressing land degradation and C emissions, implementation of Integrated Farming system (IFS) is recommended. IFS employs a holistic approach encompassing livestock management, provision of ecosystem services and development of resilient and adaptable farms. These systems enable farms to effectively respond to climate variations by diversifying plant species and employing varied land resource management strategies. IFS integrate crops, livestock, aquaculture and other activities within a single farm. These multifaceted systems demonstrate higher productivity, greater resilience to environmental changes and reduced adverse impacts compared to simpler farming models. The inclusion of trees and legumes enhances species diversity and farm resilience, while also contributing to GHG emission reductions. The foliage from certain trees and legumes improves the nutritional intake of farm animals, which in turn reduces methane emissions per unit of product, thereby decreasing overall emissions. This approach is particularly beneficial for small holder farmers, who play a vital role in India's agriculture sector.

Water smart farming

Effective water management is crucial for agriculture globally due to declining groundwater levels and increasing freshwater pollution. In response to climate change, farmers are adapting their water usage practices by implementing strategies such as rainwater harvesting and the combined use of groundwater and surface water. To ensure the sustainability of water resources, it is essential to employ appropriate irrigation techniques. In India, farms in arid regions are adopting micro-irrigation systems, including drip and sprinkler systems, to address water stress exacerbated by climate change. This initiative is part of the National Mission on Micro-Irrigation. Reports indicated that micro-irrigation systems can achieve energy savings

Integrated farming System

Various Components of IFS

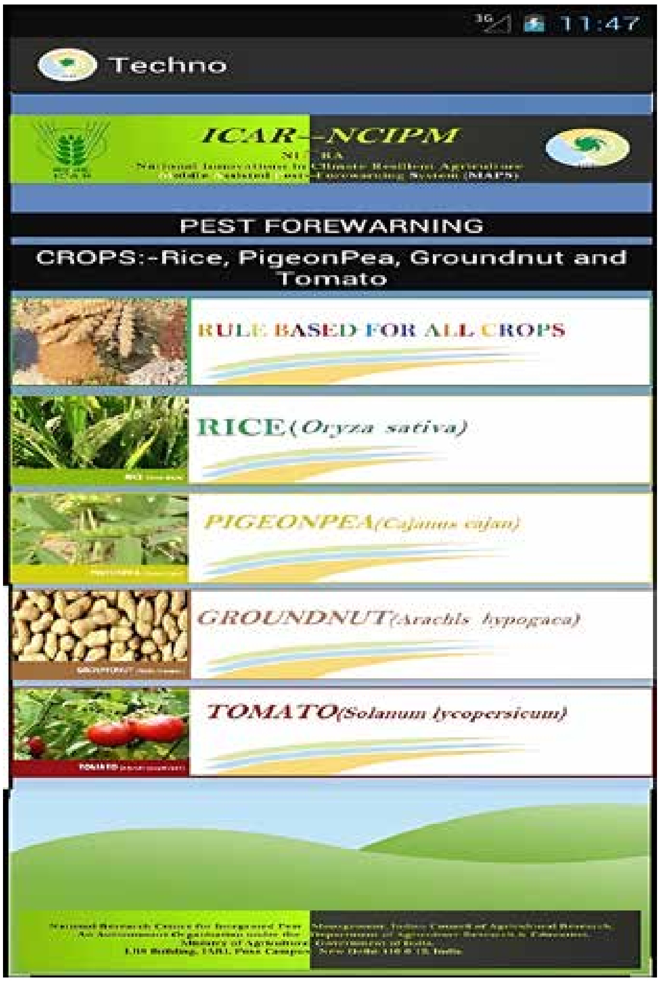
by 39%. Rainwater harvesting, a traditional method in arid regions, remains a valuable practice for water conservation. The integration of rainwater harvesting in farm ponds and community tanks can enhance crop production. Additionally, strengthening existing watersheds through various farm-level measures can mitigate the impacts of climate change and drought, thereby enhancing resilience in drought-affected areas.

Digital tools

Precision agriculture represents a significant advancement in farming, leveraging cutting-edge technology to enhance sustainability. This approach enables farmers to increase profitability while minimizing resource usage and environmental impact. The implementation of Decision Support Systems facilitates farm management by utilizing tools such as GPS, drones and satellite imagery to create maps that illustrate variations in crop yields, soil types and moisture levels. Sensors play a crucial role in data collection, contributing to improved crop yields and energy conservation, thereby promoting a sustainable future. By adhering to sustainable practices, precision agriculture optimizes crop management with reduced reliance on fertilizers, pesticides and other limited resources such as water and energy. Automated systems monitor and irrigate crops, employing sensors to assess soil conditions, including temperature and moisture. This data informs decisions regarding water and fertilizer application. Additionally, sensors measure soil moisture, which is vital for effective irrigation and enhanced crop growth. The integration of robotics, automated systems, and artificial intelligence has significantly advanced modern agriculture. Drones are becoming integral to environmentally sustainable farming practices. In precision agriculture, drones equipped with sensors perform various tasks, including soil and field analysis, crop monitoring, spraying of pesticides and crop health assessment. This technology enables precise soil management, encompassing soil organisms and plant inputs, based on real time monitoring of soil, crops and environment. Android based applications are also developed which assist in location specific forewarning of pests in different crops.

Renewable energy sources

The agriculture sector is heavily reliant on fossil fuels for food production, posing significant threats to food security and sustainable practices. Traditional farming methods that utilize fossil fuels contribute to environmental pollution through GHG emissions. Reducing fossil fuel consumption would decrease GHG emissions and transitioning to renewable energy could decouple energy use from GHG emissions. Future agricultural practices must incorporate renewable energy and nutrient recycling to mitigate energy expenses and combat global warming. Renewable energy is derived from inexhaustible natural sources such as sunlight,



Mobile app for pest forewarning

wind, water and geothermal heat, which are particularly advantageous in rural areas. Utilizing renewable energy in agriculture can enhance food, environmental and social security, resulting in increased profitability and autonomy for farmers.

SUMMARY

The implementation of CRA practices encounters challenges even with existing government policies and initiatives. To effectively promote CRA across India, a long term strategy is essential. These insights can aid in formulating strategies for Indian agriculture aligning it with sustainability and the SDGs. Climate smart villages represent a viable approach to expanding adaptation options. Locations specific conservation strategies for water efficient farming such as cover crops and rainwater harvesting can be promoted with farmers demonstrating these technologies in their fields. Different climate change initiatives like NMSA, NICRA, NDMA can be integrated with national agricultural policies on food security, disaster management and natural resource conservation. A multi-intervention approach including crop management practices is necessary to promote climate resilient crops. The dissemination of knowledge on adaptation and mitigation measures among stakeholders is crucial for broader acceptance. A comprehensive CRA approach can contribute to achieving the sustainable agenda objectives as many SDG goals address climate change agriculture production, natural resource conservation and food security.

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Integrated farming systems for enhancing productivity and livelihood of small farmers

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Integrated Farming System (IFS) offers a viable solution by integrating multiple enterprises. The by-products of one enterprise serve as valuable inputs for another, thereby fostering resource recycling, labour use efficiency, and reduced market dependency. By promoting year-round productivity, IFS significantly improves livelihood security. IFS minimizes risks from crop failures, market fluctuations, and impacts of climatic variability. Thus, IFS is a resilient, and farmer-centric model, particularly suited to the needs of small and marginal farmers in India. Despite challenges of investment, management, and market linkages, the long-term economic, nutritional, and ecological benefits establish IFS as a cornerstone for sustainable agriculture in India.

Keywords: Enhanced income and livelihoods, Enterprise diversification, Integrated farming systems, Nutrient cycling

THE rapid growth of the global population has placed unprecedented pressure on the agricultural sector, compelling a paradigm shift in food production systems. Traditionally, agricultural research and technologies were tailored for large, mechanized farms, often leaving smallholders at a disadvantage. This technological divide has widened the gap between large landowners and small and marginal farmers. Globally, more than 80% of farmers fall into the smallholder and marginal category, who struggle to achieve livelihood security despite significant progress in global food security. India alone contributes nearly one-fourth of the world's small and marginal holdings, with the majority cultivating less than 2.0 hectares of land. For these farmers, raising income and ensuring sustainable livelihoods remain persistent challenges for researchers, policymakers, and governments. Given that land resources are finite and further horizontal expansion of cultivated area is practically impossible, focus must shift towards vertical intensification through diversification. The Integrated Farming System (IFS) offers a viable solution in this direction by integrating multiple farming enterprises such as crops, dairy, poultry, fisheries, horticulture, and others within a single farm unit. The by-products of one enterprise serve as valuable inputs for another, thereby fostering resource recycling, labour use efficiency, and reduced market dependency. By promoting year-round productivity, optimal resource utilization, nutrient recycling, and income diversification, IFS significantly improves livelihood security. Furthermore, the diversity embedded in IFS minimizes risks from crop failures, market fluctuations, and climatic variability. As such, IFS represents a sustainable, resilient, and farmer-centric model, particularly suited to the needs of small and marginal farmers in India and across the globe.

Need of IFS

The urgency of adopting IFS arises from multiple socio-economic and ecological challenges faced by smallholder agriculture.

- ***Declining landholdings:*** Fragmentation of agricultural land continues to rise. Presently, approx. 85% of Indian farmers fall under the small and marginal category, collectively operating just 44.6% of the total cultivated area.
- ***Self-sufficiency:*** IFS promotes self-reliance among small and marginal farmers by producing food, fodder, fuel, and income within the farm boundary.
- ***Year-round employment:*** By integrating multiple components, IFS generates continuous employment opportunities for farm families throughout the year.
- ***Efficient resource utilization:*** The system ensures optimal use of available natural, human, and financial resources without diminishing the overall farm value.
- ***Curbing rural-urban migration:*** By improving profitability and livelihood security at the village level, IFS helps reduce distress migration of smallholders to urban centers.
- ***Sustainability and risk management:*** The multi-

enterprise approach enhances ecological balance, reduces dependency on external inputs, and builds resilience against climate and market uncertainties.

Components of IFS in India

IFS in India incorporates both basic and supplementary components, tailored to regional resources, farmer needs, and agro-climatic conditions.

Basic components (Core enterprises found in most systems):

- **Cropping system:** The foundation of all farming systems, present in almost every model.
- **Dairy:** The second most important component, integrated in nearly 83% of farming systems.
- **Horticulture (fruits and vegetables):** Enhances dietary diversity, nutritional security and higher returns.
- **Fisheries:** Vital in water-rich and coastal regions.
- **Poultry:** Provides quick returns and supplements household earnings.

Supplementary Components (value-adding enterprises):

- **Apiculture (Beekeeping):** Enhances pollination and provides honey.
- **Vermicomposting:** Ensures organic manure for crops and reduces input costs.
- **Boundary plantation:** Strengthens ecological services and adds income.
- **Biogas units:** Convert animal waste into renewable energy while supplying nutrient rich slurry for enhancing soil fertility.

Across India, nearly 25 types of farming systems have been documented, developed through various permutations and combinations of farming enterprises. Among these, seven major systems account for nearly 76% of the total share nationwide. The most dominant and widely adopted system is the crop + dairy combination, practiced by approximately 42% of farmers. This is followed by crop + dairy + horticulture, which contributes 11%, while crop + dairy + goatry accounts for 7%. A more diversified model, crop + dairy + goatry + poultry, represents about 5% of the systems.

Crop diversification in IFS for higher income and nutritional security

Crop rotation is one of the basic principles of the IFS. IFS encourages the cultivation of multiple crops, including cereals, pulses, oilseeds, vegetables, and fruits. This diversification reduces the risk of crop failure due to climatic uncertainties and ensures a continuous supply of food. In an IFS model, cereals such as wheat, rice, maize, and millets form the backbone of staple food production, ensuring household food security. These are strategically combined with pulses like pigeon pea, chickpea, mung bean, urd bean, etc. which contribute significantly to dietary protein intake and improve soil fertility through biological nitrogen fixation. Oilseed crops such as mustard, groundnut, sunflower, and sesame enhance dietary diversity and market opportunities while helping to disrupt pest and disease cycles in rotations. Fodder crops such as Napier-Bajra hybrid, berseem, and sorghum are integrated to support livestock units and reduce dependency on external feed purchases. Proper crop sequencing and intercropping not only maximize land use efficiency but also improve soil health through diverse root architectures and residue incorporation.

Horticulture: Fruits and vegetables

Horticultural crops significantly enhance both income and nutritional security. Incorporating seasonal vegetables such as tomato, brinjal, okra, cucurbits, and leafy greens into the IFS ensures a steady cash flow and dietary diversity. Perennial fruit crops like mango, guava, jackfruit, papaya, and banana contribute to long-term income stability while improving farm biodiversity. Vegetables grown in sequence—*kharif, rabi,* and summer seasons, ensure year-round production and market availability. The integration of protected cultivation, micro irrigation, and improved hybrids further boosts productivity, while market-oriented varieties help smallholders capture better prices.

Livestock and fisheries enterprises

Livestock rearing and fisheries are vital components of IFS, especially in the Indo-Gangetic Plains (IGP) where protein deficiency is widespread. Dairy is the cornerstone enterprise, providing regular income through daily milk sales. Regionally suited high-yielding crossbred cows, buffaloes, or indigenous breeds are selected, and their productivity is enhanced through balanced ration, mineral supplementation, and hygienic housing. Poultry, whether backyard or semi-intensive, offers quick returns, supplying eggs and meat for both household use and market sales. Goat rearing and duckery can also be integrated where grazing lands and water bodies are available. These enterprises efficiently recycle crop residues, weeds, and kitchen waste efficiently, reducing feed costs while contributing to nutrient recycling via manure.

Fisheries complement IFS wherever water resources exist. Farm ponds or reservoirs can be stocked with species such as rohu, catla, mrigal, and tilapia under polyculture systems. Integrating aquaculture in waterlogged or low-lying areas enhances productivity of marginal lands. Fish farming not only supplies high-quality protein but also optimizes resource use by utilizing farm wastewater and enabling integration with duckery or horticulture along pond embankments. Composite fish culture maximizes ecological niche utilization, improving yield per unit area.

Nutrient recycling and vermicomposting

A critical strength of IFS lies in internal nutrient cycling. Crop residues, livestock manure, poultry droppings, and agro-wastes are recycled into compost or vermicompost, reducing reliance on costly chemical fertilizers. Vermicomposting using species like *Eisenia fetida* produces nutrient-rich organic manure that improves soil structure, water-holding capacity, and microbial activity. Similarly, farmyard manure (FYM) and enriched compost supply macro- and micronutrients, ensuring sustainable soil fertility management. These organic inputs promote nutrient recycling, minimize environmental pollution and support a closed-loop farming system.

Boundary plantation

Planting fruit-bearing and multipurpose species along farm boundaries optimizes land use while providing ecological and economic benefits. Karonda (*Carissa carandas*), jackfruit (*Artocarpus heterophyllus*), and guava (*Psidium guajava*) are well-suited for boundary plantations in many agro-climatic zones. These species offer seasonal fruits for home consumption and sale, provide shelterbelts against wind, and support pollinator diversity. The perennial nature of these plants ensures long-term income without compromising the primary cropping area.

Mushroom production

Mushroom cultivation is an emerging component in IFS with high returns from a small area. Species like oyster (*Pleurotus spp.*), button (*Agaricus bisporus*), and milky mushroom (*Calocybe indica*) can be grown using crop residues such as wheat straw, paddy straw, and maize cobs. Besides being a nutrient-rich food source, mushroom cultivation creates employment opportunities for family members, especially women. Post-harvest spent mushroom substrate can be used as organic manure, further enriching the nutrient cycle within the farm.

Multilayer vegetable farming

Multilayer farming involves growing compatible vegetable crops at different canopy levels to maximize sunlight interception and land productivity. For instance, creepers like bitter gourd or bottle gourd can be trained on trellises above shorter crops like okra or amaranthus, with root vegetables like radish or carrot underneath. This system ensures higher yields per unit area, diversified income sources, and efficient utilization of space and resources. In IFS, multilayer farming is particularly effective in homestead gardens and peri-urban areas where land is limited.

IFS as a pathway to nutritional well-being

While food security ensures availability and access to food, nutritional security focuses on dietary quality and diversity. In IGP despite high agricultural output, malnutrition remains due to limited dietary diversity and over-reliance on staples like wheat and rice. IFS bridge this gap by delivering a balanced food basket rich in proteins, vitamins, minerals, and other essential nutrients.

Diversifying the farm, diversifying the plate

IFS integrates cereals (supply carbohydrates), pulses (provide proteins and micronutrients), vegetables, and fruits (offer vitamins, antioxidants, and dietary fiber) to create a nutrient-rich diet. This crop diversity ensures farming families and communities enjoy balanced meals throughout the year.

Organic practices for healthy and safe produce

By using farmyard manure, crop residues, and compost from livestock waste, IFS promotes organic farming. This reduces chemical residues in food, safeguards consumer health, and enhances soil fertility for long-term productivity.

Combating hidden hunger through nutrient-dense crops

Micronutrient deficiencies ("hidden hunger") are a major concern in rural IGP. Inclusion of crops such as millets, leafy greens, and fruits in IFS helps tackle this. For instance, iron-rich spinach and vitamin C-rich citrus fruits grown alongside staples can reduce anaemia and micronutrient deficiencies.


Round the year fodder production in IFS at Western Uttar Pradesh for livestock improvement

Promising interventions at farmer's field (A) Azolla for animal feeding (B) Bundur Sheep (C) Duplex for backyard poultry (D) Improved shed for goatry (*Photo courtesy*: AICRP-IFS-OFR)

Implementation on a small scale

High implementation costs limit the direct replication of IFS models. However, the Indian Institute of Farming Systems Research (IIFSR), through its scheme AICRP-IFS-OFR, has demonstrated that strategic, region-specific interventions can significantly enhance smallholders' livelihoods. By focusing on limited yet targeted interventions tailored to specific modules and local conditions, the programme showcases the potential for scalable solutions that improve productivity and profitability of small farms across diverse agro-climatic zones. Under the AICRP-IFS-OFR on-farm research component, IFS interventions were refined with farmer participation. These refinements were based on location-specific, module-based, low-cost practices designed to strengthen food security, nutrition, environmental sustainability, and income for small and marginal farmers. The refinements covered four key modules:

- ***Benchmarking:*** Recording baseline data on crops, livestock, other farm components, and the household as a whole.
- ***Cropping system diversification/improvement:*** Introducing efficient cropping systems suited to farmers' resources, preferences, and market opportunities, while improving existing practices.
- ***Livestock diversification/improvement:*** Promoting year-round fodder production, mineral mixture supplementation, deworming, and integration of low-cost, location-specific components such as backyard poultry, duckery, piggery, and goat rearing.
- ***Product diversification:*** Supporting value addition through preparation of mineral mixtures, processing of market surplus products, and promotion of kitchen/roof gardens.

Across the country, a total of 73 farming systems were refined through these farmer-participatory approaches. Interventions were made in critical inputs with an average cost of ₹7,889 per system. Net returns varied widely—from ₹4,786 at Mandla (Madhya Pradesh) to ₹1,87,994 at Alappuzha (Kerala). On average, net returns rose to ₹55,573 per system, representing an 86% increase within the second year of intervention.

Economic advantages of IFS

- ***Enhanced and stable farm income:*** Diversification through IFS ensures multiple and complementary income reducing farmers' vulnerability to market volatility and climatic uncertainties. For instance, earnings from livestock, aquaculture, or high-value horticultural produce can buffer losses from staple crop failures, ensuring year-round revenue flow.

- ***Rural employment and livelihood security:*** The multifaceted nature of IFS demands skilled and unskilled labour for activities such as animal husbandry, fish rearing, and intensive crop management. This not only generates substantial on-farm employment but also curbs rural-to-urban migration by creating sustainable livelihood opportunities within villages.
- ***Reduction in production costs:*** Efficient recycling of crop residues, livestock manure, and other farm by-products within the IFS framework significantly minimizes dependence on external inputs such as synthetic fertilizers and pesticides. This integrated resource-use strategy lowers input costs while maintaining soil fertility and ecological balance.

Environmental benefits of IFS

IFS contribute not only to food and nutritional security but also to environmental sustainability through the following pathways:

- ***Building living soils:*** Inclusion of legumes, agroforestry components, and organic inputs improves soil fertility, stimulates microbial activity, and reduces risks of land degradation.
- ***Securing every drop:*** Practices such as rainwater harvesting, efficient irrigation, and tree-based systems minimize water losses and enhance groundwater recharge.
- ***Locking away carbon:*** Agroforestry and organic management increase carbon sequestration potential in IFS, thereby mitigating climate change impacts.

Challenges in IFS adoption

Despite its potential, IFS adoption faces several challenges. Initial investment in infrastructure for multiple enterprises can be high for resource-poor farmers. Management complexity increases as multiple components require knowledge, labour, and timely interventions. Market access for perishable produce, lack of extension services, and absence of integrated value chains often limits profitability. Climatic uncertainties, pest pressures, and fragmented landholdings further hinder adoption. Addressing these challenges require targeted policy support, capacity building, and farmer-to-farmer learning models.

SUMMARY

Integrated farming systems offer a resilient pathway for small and marginal farmers to achieve higher productivity, diversified income, and enhanced livelihood security. By integrating crops, livestock, fisheries, horticulture, boundary plantations, mushrooms, and multilayer vegetable farming with efficient nutrient recycling, farmers can optimize resource use and ensure year-round returns. Although challenges remain in terms of investment, management, and market linkages, the long-term economic, nutritional, and ecological benefits establish IFS as a cornerstone for sustainable agriculture in India.

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Regenerative agriculture: A pathway to restoring soil quality and improving crop performance

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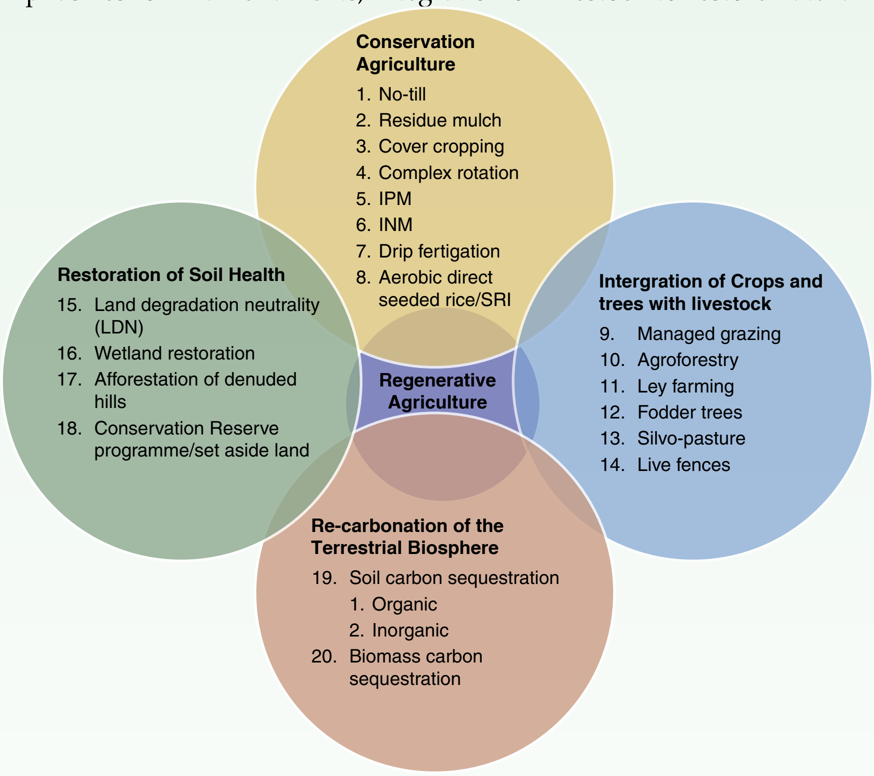
Regenerative agriculture offers a sustainable pathway to restore soil quality, and improve crop performance by integration of diverse practices i.e. no-tillage, crop diversification, cover crop, agro-forestry and organic amendments. These practices enhance soil structure, water retention, infiltration, nutrient cycling and microbial activity leading to resilient cropping systems with stable yields. Scientific evidences from different land use systems revealed its role in decreasing input dependency, mitigating climate change through C sequestration and strengthening ecosystem services. Thus, it provides a holistic approach for long-term agricultural productivity and environmental sustainability.

Keywords: Cover crop, Crop diversification, Regenerative agriculture, Soil quality, Sustainability

REGENERATIVE agriculture (RA) is an ecologically grounded farming strategy that emphasizes on improving biodiversity, rebuilding soil health, increasing ecosystem resilience, improving nutrient cycling, sustaining crop yield, and restoring landscape functions while preserving or enhancing farm profitability. The approach of RA is based on sets of guiding principles and objectives where practitioners of RA uses various tactics that integrate ecological and biological processes with the aim of increasing agricultural production and restoring soil quality and landscape functionality. The objective of RA is not to restore the native pre-agriculture biology and ecology functions, but to leverage ecological processes in nature with the agriculture systems to enhance farming system health. Unlike the conventional practices that degrade soil fertility and structure through intensive tillage, injudicious use of fertilizers and other agro-chemicals, mono-cropping and faulty irrigation practices, RA employs agricultural practices such as conservation agriculture (CA), crop diversification, cover cropping, use of organic amendments, integration of livestock to restore natural



Basic tenets of regenerative agriculture designed to draw CO_2 from the atmosphere (*Source*: Lal 2020).

soil processes. The term "regenerative agriculture" was coined by Gabel in 1979, then Rodale further developed the concept of RA organic farming to include various options that encompass a holistic approach with a focus on social and environmental improvements without the use of synthetic fertilizers and other agro-chemicals. Since then, scientific studies have demonstrated that RA can significantly enhance soil physico-chemical and biological attributes. According to Food and Agricultural Organization (FAO), RA practices have adopted the practices to go beyond the "do no harm" principles of sustainable agriculture.

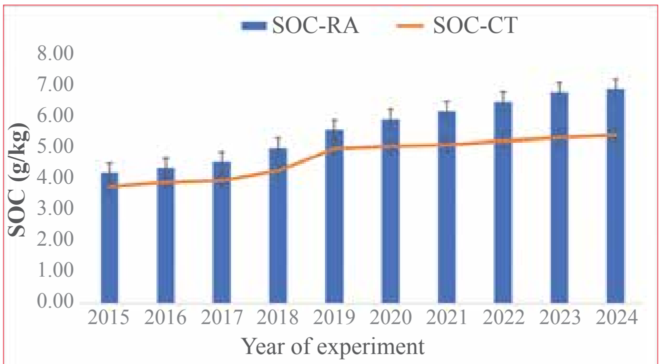
Table 1. Regenerative agriculture's principles, practices and purported benefits and mechanisms to improve soil health

RA Principles	RA Practices	RA Benefits	Microbial Mechanisms
• Minimum soil disturbance • Keep living roots in soil year round • Limited use of chemicals • Keep soils covered • Integrate livestock • Encourage diversity	• No/minimum tillage • Diverse crop rotation • Stubble retention • Multispecies cover • Composting and use of biostimulants • Intercropping • Rotational grazing • Reduce synthetic inputs	➢ Improved soil health through • Improved microbial functions • Increased soil carbon • Improved soil moisture • Improved resilience to pest and disease ➢ Nutrient rich food ➢ Reduced greenhouse gas emissions	• Liquid carbon pathway • Enhanced soil aggregation, plant growth and photosynthesis • Improved uptake of water and minerals

The six principles of RA help in preventions of soil erosion and depletion, provide appropriate nutrients to the crops with minimum external inputs, actively build the soil, produce healthy, high yielding crops with limited weeds and pests' incidences, increase farmers financial returns, minimize the greenhouse gas emissions from agriculture, and improve the human health. The major goal of RA is to capitalize on natural processes through, capturing environmental carbon dioxide (CO_2) through photosynthesis, improved symbiotic soil-plant-microbial interaction, enhancing soil structure and water retention through biological means, integration of livestock with positive impact on ecosystem services. For better results and long-term sustainability, RA practices should align with climatic, social and environmental factors i.e. temperature, precipitation, soil type, markets, farm enterprise mix, and individual preferences.

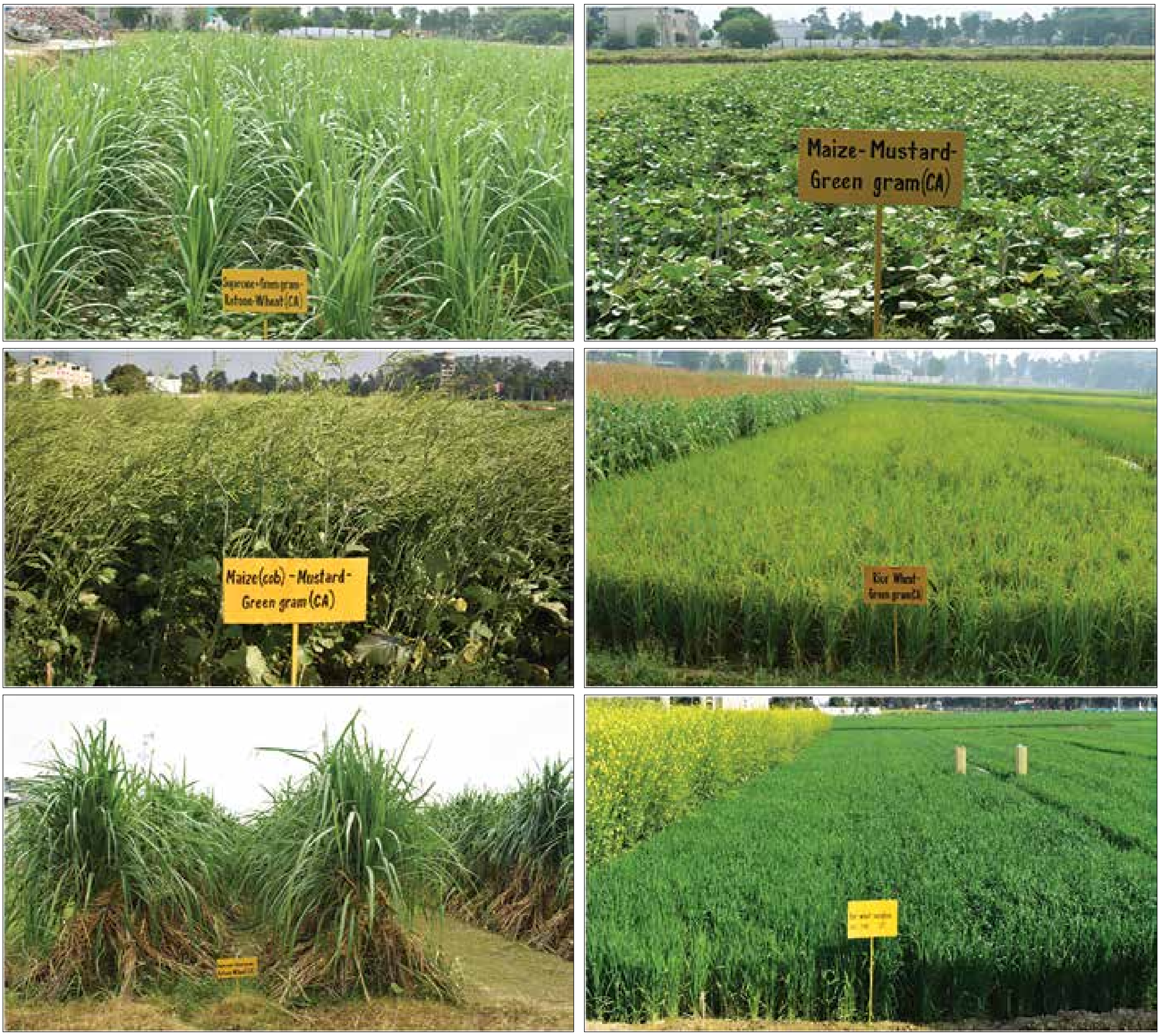
RA practices for improving soil health/quality

Soil quality/health is defined as the ability of soil to continue function as a vital living system within ecosystem and land-use boundaries, while sustaining biological productivity, maintaining water and air quality, and promoting plant, animal and human health. The soil health is attributed to its desirable soil physico-chemical and biological attributes that supports healthy productive crops. The RA practices primarily focuses on improving soil organic matter and boosting its fertility and productivity. Soil organic carbon (SOC) is crucial for improved soil structure, fertility, aeration, nutrient availability, water holding capacity and water infiltration, solution for mitigating climate change. The RA practices such as no-tillage combined with multi-species cover crops, can improve SOC by 0.3–1.0 Mg C/ha/yr and enhance water retention by 15–20%. Further, an annual improvement of 0.4% SOC in 30–40 cm soil layer in all land uses can significantly absorb CO_2 emitted from human activities, while providing co-benefits of improved food security and soil health. Long-term adoption of RA practices can offset 33 Pg SOC losses in different land use systems. In India, trials under Consortium Research Platform on Conservation Agriculture (CRP CA) have shown that integrating no-till/reduce tillage and legumes in different cropping systems increased SOC by 23–29% over a decade. The CA practices i.e. zero tillage, permanent cover and crop diversification which are an integral part of RA, significantly improve the C stock, C-accumulation, and C-sequestration compared to conventional practices. Minimum tillage, a key practice in RA, aims to promote microbial proliferation, thus enhancing nutrient cycling in the soil. Minimum or no-till coupled with residue retention in different cropping systems is a promising management strategy to improve SOC stock, increased biological activity and resilience to harsh weather conditions. Long-term adoption of no-tillage in different landuse systems could improve the C stock around 4.6 Mg/ha in 0–30 cm soil layer over a period of 10 years.



Changes in soil organic carbon over the years in RA and CT practices

Further, long-term adoption of no-till/zero-tillage (NT/ZT) in various land use systems across the Indo-Gangetic Plain of India has shown an improvement of 12–20% in SOC content in the top 0–10 cm soil layer. In addition to SOC enhancement, NT promotes soil aggregation (30–40% improvement) by minimizing soil disturbance. This improved soil aggregation further protects soil organic matter within the soil aggregates.



Performance of different crops in RA based management practices

Soil moisture and infiltration are significantly improved under the NT system due to maintenance of continuous pore networks. NT system reported to increase infiltration rates by 30–50% and soil moisture retention by 25–32% compared to conventional tillage. A long-term study in the Upper Indo-Gangetic Plain (UIGP) demonstrated that adoption of NT practices saved 15–20% irrigation water in the rice-wheat system compared to CT. In addition to SOC improvement, enhanced root proliferation in the NT improves nutrient uptake. Furthermore, NT coupled with crop residue retention improves the available nitrogen, phosphorus, potassium and sulphur by 10–26% in 0–15cm soil layer. Soil biological activity is significantly improved by NT including soil microbes, fungi, actinomycetes, extracellular enzymes and earthworms. A long-term study of 11 years in UIGP showed 40–60% higher soil microbial biomass C and N in NT systems compared to CT. Agroforestry, a key component of RA other than CA practices, plays significant role in improving soil SOM, water retention, nutrient cycling and reducing soil erosion, thus ensure long-term agricultural sustainability and ecosystem functions. Livestock have been an integral part of agriculture since ancient time. Integration on livestock with crops/grazing cover crops have shown a significant improvement in soil health. Studies conducted across the different agro-ecosystems recorded an improvement of soil health index (up to 0.58–0.66 m layer) with crop-livestock integration both in pasture and other land use systems. Likewise, long-term studies (>15 years) for organic manures and their role in regenerative agriculture under different types of soils in India and globe improved SOC by 9.1–11.0%, N (4.0-16.4%), K (9.9-20.3%) and crop phosphorus by 3.56 kg/ha. Crop and soil management approaches i.e. cover cropping and green manuring, crop diversification and rotations, contour farming, terracing and buffer strips are other nature-based approaches which are crucial for sustainability of RA practices. Studies on these practices recorded 0.1–0.3% per year improvement in SOC, and 40–70% reduction in soil erosion.

RA practices and crop performance

The RA practices have shown a significant positive impact on crop yields and profitability, although the extent of benefits depends on local agro-climatic conditions, crop and soil factors. The RA practices generally lead to enhancement in crop yields and performances, primarily through improved soil health and increased climate resilience. The RA practices build SOM, improving soil nutrient and water retention, enhanced microbial activity, all which benefits the crops during the adverse conditions. The RA practices i.e. NT in conjunction with cover crops/residue retention and crop diversification has potential benefits on crop performance through enhancement in the long-term C sequestration, soil quality, greater resilience to production system to climate change related aberrations, mitigation in greenhouse gas emissions and improved environmental sustainability. Additionally, these practices reduce weed incidences, enhance nutrient and water use efficiency, and prevent crop residue burning. Long-term studies in IGP have shown significant improvement by 20%, 17.7%, 16.6% and 21.4% in maize, mustard, wheat and greengram yield, respectively under RA-NT/ZT systems compared to conventional system. Residue management, crop diversification with inclusion of summer greengram in rice-wheat system can enhance the system productivity by 0.5–1.2 Mg/ha/yr under RA practices. Thus, as a result of its potential to mitigate climate change and improvement in crop yield, regenerative agriculture is recommended as an effective climate-smart agriculture management practice. Scientific evidences from different land use systems across the globe has proven that RA practices promote crop diversification, through inclusion of legumes and agroforestry which stabilize crop yields under climatic stress and it can deliver up to 19% higher crop yields under the drought conditions as compared to monoculture. In south Asia, even replacing rice with maize or pulses under RA system can improve the system productivity by 20–25%.

SUMMARY

Regenerative agriculture is an ecological approach to restore soil health, biodiversity, and crop performance. Practices such as no-tillage, crop diversification, cover cropping, organic amendments, and agroforestry improve soil organic matter, water retention, and nutrient cycling. These methods reduce erosion, enhance microbial activity, and increase resilience against climate stresses. Scientific studies from the IGP and other regions show yield stability and higher input-use efficiency under regenerative practices compared to conventional farming. By sequestering carbon and enhancing ecosystem services, regenerative agriculture not only boosts farm productivity but also contributes to climate change mitigation and long-term sustainability. Thus, regenerative agriculture serves as a sustainable pathway to maintain soil quality, ensure food security, and support long-term farm profitability.

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Organic Farming: Growth and market opportunities in India

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Conventional farming has played a vital role in ensuring food security in India through the use of high-yielding seeds, irrigation, fertilizers, and agrochemicals. While these practices have boosted productivity, their excessive reliance has led to serious concerns such as declining biodiversity, deteriorating soil and environmental health, unsafe food, and reduced farm income. Pesticide residues in many crops have often exceeded safe limits, posing risks to human health and the environment. Overuse of chemicals has also contributed to soil, water, and air pollution. To address these challenges, alternative approaches have emerged, including integrated crop management, conservation agriculture, integrated farming systems, agroforestry, and organic farming. These sustainable methods focus on improving productivity while conserving natural resources and ensuring safer food, thus reducing the negative impacts of conventional.

Keywords: Marketing, Organic farming, Organic production, PGS

ORGANIC farming is founded on the strict prohibition of synthetic pesticides, fertilizers and other chemicals, and genetically modified organisms (GMOs). It thus ensures that crop production remains safe, natural, and environmentally friendly. A big thrust is given on biodiversity, both above and below ground. This involves protecting and enhancing crop diversity, supporting beneficial insects and pollinators, as well as maintaining rich soil biodiversity through microorganisms and earthworms, all of which contribute to a balanced and resilient agroecosystem. Organic farming relies chiefly on natural cycles to sustain productivity, drawing upon ecological processes such as nutrient cycling, biological nitrogen fixation, and the natural balance between pests and their predators. Rather than relying on external synthetic inputs, these ecological processes ensure greater stability and resilience within the farming system. Equally significant is the practice of nutrient recycling, in which crop residues, compost, animal manure, and other organic materials are incorporated back into the soil. This approach not only restores soil fertility, but also improves soil structure, strengthens its moisture-holding capacity, and sustains long-term agricultural productivity.

Key components

Organic farming is built on four fundamental pillars, viz. organic standards, certification, technology package, and marketing which together define its philosophy and practice. These pillars act as the foundation of the system and hold universal relevance for all stakeholders, including farmers, students, teachers, trainees, academicians, policymakers, planners, and the wider public interested in sustainable agriculture.

Pillars of organic farming (*Source*: Generative AI 30-08-2025)

Familiarity with these guiding components is crucial for appreciating the holistic nature of organic farming and for ensuring its effective adoption, promotion, and policy support.

In a broader perspective, these four pillars can also be regarded as the curriculum or syllabus of organic farming, offering a structured framework to understand it's ecological, economic, and social dimensions. Much like an academic syllabus outlines essential areas of learning, these pillars highlight the knowledge and practices required for successful implementation. By aligning teaching, learning, and practice around them, organic farming can be systematically advanced and effectively mainstreamed into sustainable food systems.

Organic standards: Organic standards refer to the clearly defined rules and regulations that guide the production, processing, and labelling of organic products. These standards specify how organic produce should be cultivated, what practices and materials are permitted in crop production and other agricultural enterprises, and the procedures for converting conventional farms into organic systems. They also establish the framework for labelling and certification to ensure authenticity and consumer trust. In essence, organic standards serve as the foundation of organic farming, providing uniform guidelines that safeguard both producers and consumers. For detailed information, one may visit the official Agricultural and Processed Food Products Export Development Authority (APEDA) website: https://npop.apeda.gov.in/

Certification or regulatory mechanism: Organic certification is a formal process designed to verify and ensure that producers of organic food and agricultural products adhere to the prescribed organic standards. Broadly, any business directly involved in the food chain including seed suppliers, farmers, food processors, retailers, and even restaurants can obtain organic certification. While specific requirements vary across countries, certification generally involves compliance with a defined set of production standards covering cultivation practices, storage, processing, packaging, and transportation.

In India, two types of certification systems are operative. The first is Third-Party Certification, implemented by APEDA under the National Programme for Organic Production (NPOP) (https://npop.apeda.gov.in/). In this system, the producer acts as the first party, the consumer as the second party, and the certification body as the third party, hence the name. The second system of certification is the Participatory Guarantee System (PGS), which is a community-based approach to certification. This method is implemented by the National Centre of Organic and Natural Farming (NCOF), Ghaziabad (https://pgsindia-ncof.gov.in/). Together, these mechanisms provide credibility to organic produce and build consumer confidence in the integrity of organic products.

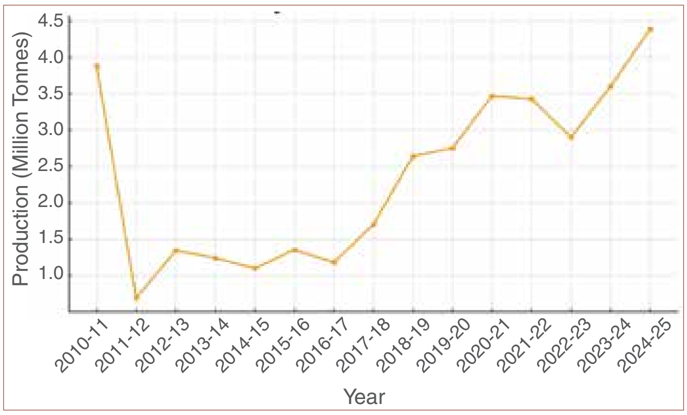
Technology package: Technology package involves the techniques/methods of producing, processing and value addition of various organic products. For example, in case of organic crop production, it involves right time of sowing, selection of appropriate varieties/seeds, sowing distance, sowing depth, seed rate, seed treatment, sowing/planting methods, nutrient management, water management, weed management, crop protection from diseases and insects, harvesting, and post-harvest management, etc. Due care is required as the management of crops at organic farms is quite different from that at conventional farms. The inputs used to grow the crops are different at organic farms.

The technology packages for growing organic crops are still evolving in different parts of the country. For further details, websites of NCONF, Ghaziabad and All India Network Project on Organic Farming (AINPOF), ICAR-Indian Institute of Farming Systems Research, Meerut, UP (https://iifsr.icar.gov.in/ai-npof.html), concerned ICAR institutes and State Agricultural Universities (SAUs). Number of crops can be grown successfully by adopting organic methods of cultivation.

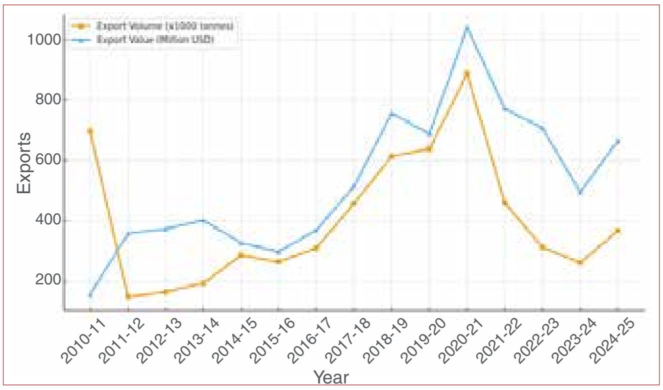
Market network: The organic farming market in India encompasses both inputs and outputs. Inputs such as farmyard manure, compost, vermicompost, oilcakes, biofertilizers, and biopesticides are widely marketed to support cultivation. Outputs, including raw and processed products, reach consumers through diverse channels. Small and medium farmers rely on direct sales via farmers' markets, farmgate sales, CSAs, and online platforms, ensuring transparency and reduced intermediaries. Larger producers use formal supply chains involving wholesalers, retailers, supermarkets, and specialty stores. India also engages in international trade, exporting certified organic products and importing selected items. Despite challenges like high prices, limited supply, and certification gaps, growing consumer demand and supportive policies signal strong expansion potential.

Growth of organic farming in India

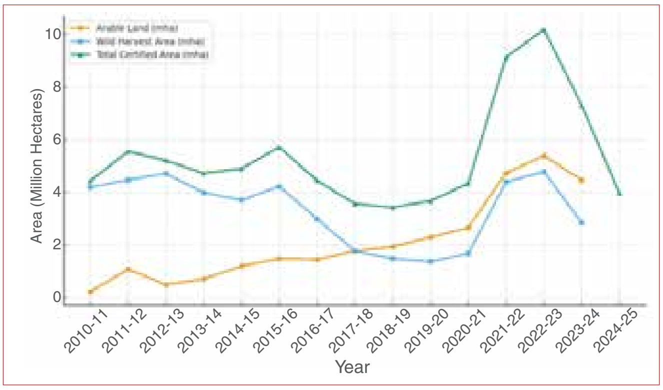
The production from organic farming in India has shown fluctuations over time, with an initial output of 3.88 million tonnes in 2010–11 that sharply declined next year. However, from 2012–13 onwards, production gradually increased and reached levels above 2.5 million tonnes by 2018–19 and 2019–20. The highest production was recorded at 3.47 million tonnes in 2020–21, and after a slight dip in 2022–23, it regained momentum to touch 4.39 million tonnes in 2024–25,



Trends of organic production (million tonnes) in India (*Source*: APEDA)



Trends of organic products export volume (x 1000 tonnes) and value (US Dollars) from India (*Source*: APEDA)



Trends of certified land area (million tonnes) under organic farming in India (*Source*: APEDA)

indicating a general upward growth trajectory despite periodic declines.

Exports of organic products also exhibit a mixed pattern. Export volumes rose consistently from 698,000 tonnes in 2010–11 to a peak of 888,000 tonnes in 2020–21, supported by a rise in export value from 157 million US dollars to over 1,041 million US dollars in the same period. After this high point, both volume and value declined significantly, with export volume falling to 261,000 tonnes in 2023–24 and value dropping to 495 million US dollars. A modest recovery occurred in 2024–25, with exports rising to 368,000 tonnes and values to 666 million US dollars, although these levels still remained below the earlier peak.

The certified arable land, which was just 0.24 million hectares in 2010–11, grew steadily to reach 5.39 million hectares in 2022–23 before reducing slightly to 4.47 million hectares in 2023–24. The wild harvest area, initially large at 4.19 million hectares, declined to about 1.37 million hectares in 2019–20, but later recovered to nearly 4.78 million hectares in 2022–23, again falling to 2.85 million hectares in 2023–24. As a result, the total certified area expanded from 4.43 million hectares in 2010–11 to a peak of 10.17 million hectares in 2022–23, before contracting to 7.30 million hectares in 2023–24. The most recent year (2024–25) shows incomplete area data but reflects a discontinuity compared to earlier trends.

The land area under organic farming at global scale increased steadily from about 37 million ha in 2010 to nearly 99 million ha in 2023, while the number of farmers rose from 1.6 million to about 4.3 million. India's share, although smaller in land area (ranging between ~3.5 to 10.2 million ha), is significant in terms of farmer participation. Indian organic farmers grew from 0.40 million in 2010 to 2.36 million in 2023, meaning India accounts for a large share of global organic farmers, currently more than half, despite having a relatively modest share of the world's organic farmland. This highlights that India's organic farming is more farmer-intensive but land-fragmented, compared to the global average.

Organic farming in India has expanded significantly, though with recent fluctuations. Production now exceeds four million tonnes annually, while exports peaked in 2020–21 before contracting and only partly recovering. Certified land area more than doubled by 2022–23, but later records show inconsistencies. Madhya Pradesh leads in certified area, followed by Maharashtra, Rajasthan, Gujarat, Odisha, Uttarakhand, Telangana, Sikkim, Uttar Pradesh, and Karnataka. Organic production spans cereals, millets, pulses, oilseeds, fruits, spices, tea, coffee, medicinal plants, and processed foods, with exports mainly to the USA, EU, UK, Canada, and Japan. Growth drivers include rising demand for safe food, export opportunities, government schemes, NGO efforts, and private sector initiatives, which together are strengthening value chains and market linkages.

Table 1. Trends in organic farming land area and number of farmers in the World and India (2010–11 to 2024–25)

Year	Total land area (million hectares) under organic farming		Number of farmers (million)	
	World	India	World	India
2010	37.0	4.43	1.6	0.40
2011	37.2	5.55	1.8	0.55
2012	37.5	5.21	1.9	0.60
2013	43.1	5.72	2.0	0.65
2014	43.7	4.90	2.3	0.65
2015	50.9	5.71	2.4	0.58
2016	57.8	4.45	2.7	0.83
2017	69.8	3.56	2.9	0.83
2018	71.5	3.43	2.8	1.15
2019	72.3	3.67	3.1	1.37
2020	74.9	4.34	3.4	1.60
2021	76.4	9.12	3.7	1.60
2022	96.4	10.2	4.5	2.48
2023	98.9	7.30	4.3	2.36

Sources: The World of Organic Agriculture (2011–2025) and https://apeda.gov.in/apedawebsite/organic/data.html

Market growth of organic inputs

The important inputs marketed in sizable quantities are organic fertilizers, biofertilizers and biopesticides in India. Regarding organic fertilizers, the base year values (2023–24) range between USD 550–586 million, with projections for 2032 spanning USD 942 million to 1.2 billion. Reported compound annual growth rates (CAGRs) vary from ~5.6% to over 10%, reflecting differences in modelling assumptions. Despite variations, all sources agree on a clear upward growth trend for organic fertilizers in India over the next decade.

Table 2. Market size and growth projections of organic fertilizers in India (2023–2032)

Sr. No.	Source	Base value in million USD (Base Year)	Projection in million USD (End year)	Compound annual growth rate (CAGR) in %
1.	Zion Market	578 (2023)	951 (2032)	~5.7%
2.	Custom Market Insights	577.1 (2023)	942.4 (2032)	5.6%
3.	Markets and Data	550 (2024)	1200 (2032)	10.23%
4.	Report on Markets	586.4 (2024)	1145 (2032)	8.73%

Sources as per Sr. No.: 1. https://www.zionmarketresearch.com; 2. https://www.custommarketinsights.com; 3. https://www.marketsandata.com; 4. https://www.reportsnmarkets.com (Accessed on 24-08-2025)

For biofertilizers, the market size estimates vary across sources, with base values ranging from USD ~100 million to 243 million and end-year projections stretching between USD 165 million and nearly 400 million. Reported CAGRs lie between 8.7% and 12%, indicating strong and steady growth in biofertilizer market.

Table 3. Market size and growth projections of biofertilizers in India (2022–2033)

Sr. No.	Source	Value in million USD (Base Year)	Projection in million USD (End year)	Compound annual growth rate (CAGR) in %
1.	TechSci Research	100.29 (2024)	165.09 (2030)	8.74 %
2.	Markets and Data	183.20 (2024)	395.86 (2032)	10.11 %
3.	IMARC Group	142.97 (2024)	399.67 (2033)	11.50 %
4.	Mordor Intelligence	242.2 (2025)	381.8 (2030)	8.90 %
5.	Fortune Business Insights	110.07 (2022)	243.61 (2029)	12.02 %

Sources as per Sr. No.: 1. https://www.techsciresearch.com; 2. https://www.marketsandata.com; 3. https://www.imarcgroup.com; 4. https://www.mordorintelligence.com; 5. https://www.fortunebusinessinsights.com (Accessed on 24-08-2025)

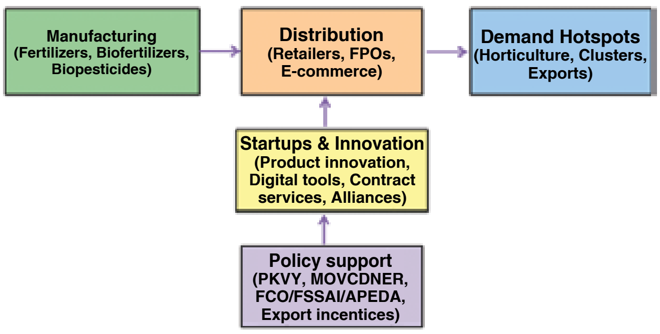
For the biopesticides market, the base year values range from USD ~70 million in 2022 to USD 260 million in 2024–25. By the end of the forecast period (2029–33), the market is expected to grow between USD 130 million and over 700 million. Reported CAGRs lie between 9.3% and 10.3%, indicating consistent double-digit growth potential. Overall, all sources highlight a strong and sustained expansion of biopesticides in India.

Table 4. Market size and growth projections of biopesticides in India (2022–2033)

Sr. No.	Source / Publisher	Value in million USD (Base Year)	Projection in million USD (End Year)	Compound annual growth rate (CAGR) in %
1.	Fortune Business Insights	69.62 (2022)	130.37 (2029)	9.38%
2.	Mordor Intelligence	242.2 (2025)	381.8 (2030)	9.53%
3.	IMARC Group	260.0 (2024)	702.3 (2033)	10.30%

Sources as per Sr. No.: 1. https://www.fortunebusinessinsights.com; 2.https://www.mordorintelligence.com
3. https://www.imarcgroup.com (Accessed on 24-08-2025)

In addition, it is evident from the data that demand for organic inputs is rising consistently and continuously. The reasons are rising area under organic farming in India, robust organic export growth, and direct support to organic clusters and input use via national schemes PKVY (Paramparagat Krishi Vikas Yojana), MOVCDNER (Mission Organic Value Chain Development for North Eastern Region) and formal quality control under FCO.



Domestic market trends and consumer preferences

Multiple analysts point to a rapidly expanding domestic market in India. The data highlights that India's organic food market is currently valued between USD 1.5–1.9 billion (2023–24), depending on the source. Despite slight differences in methodologies, all analysts project robust double-digit growth over the next decade. The market is expected to expand at a CAGR of ~20–22%, reaching between USD 9–11 billion by 2032–33. This strong growth reflects rising consumer demand for healthier, safer, and pesticide-free foods, along with supportive regulations and certification systems. Overall, the outlook is highly optimistic and favourable, pointing to a fast-evolving and promising sector in India's agri-food economy.

Table 5. India's organic food market size and forecasts

Sr. No.	Source	Base Year	Market Size (million USD)	Forecast Year	Projected Market Size (million USD)	Compound annual growth rate (CAGR) in %
1.	IMARC Group	2024	1,917.4	2033	10,807.9	20.13 (2025–2033)
2.	FAS/USDA (citing IMARC)	2023	1,600	2032	8,900	21.19 (2024–2032)
3.	EMR (Expert Market Research)	2023	1,510.36	2032	9,043	~22 (2024–2032)
4.	Market Research Future (MRFR)	2023	1,700	2032	10,329	22.2 (2024–2032)

Sources as per Sr. No.: 1. https://www.imarcgroup.com/
2. USDA. 2023. India's Organic Agriculture Sector Finds Markets at Home and Abroad. Report Number: IN2023-0095
3. https://www.expertmarketresearch.com/
4. https://www.marketresearchfuture.com/ (Accessed on 24-08-2025)

To expand the domestic market, it is always necessary to win the trust of consumer. For this purpose, 3rd party and PGS certification procedures are operative in India. To make it more robust, the Food Safety and Standards Authority of India (FSSAI) enforced the Food Safety and Standards (Organic Foods) Regulations, 2017, which mandate that organic foods sold in India must carry the Jaivik Bharat logo along with the FSSAI license number. These regulations align with certification systems like NPOP (India Organic) and PGS-India, thereby building consumer trust, ensuring authenticity, and preventing mislabelling of organic products.

Distribution channels

Organic food distribution in India operates through a multi-channel system. Direct-to-consumer models like farmers' markets, farmgate sales, CSAs, and FPO-led initiatives ensure freshness and traceability. E-commerce platforms such as BigBasket, Amazon India, and Jaivik Haat expand reach, while E-commerce players like Swiggy and Instamart deliver organic staples within minutes. Modern trade and specialty retail outlets, including Nature's Basket, offer curated organic assortments with both physical and online presence. According to estimates, supermarkets (30%) and e-commerce (25%) dominate, followed by restaurants/hotels (20%), direct sales (15%), and farmers' markets (10%), collectively ensuring accessibility, sustainability, and stronger farmer-consumer linkages.

Branding and value addition

Branding and value addition are crucial for strengthening India's organic sector by building trust, marketability, and price premiums. Certification logos such as Jaivik Bharat, India Organic (NPOP), and PGS enhance credibility and help consumers easily identify authentic products. Traceability systems like APEDA's TRACENET ensure transparency across supply chains, vital for exports and B2B trade. Value addition strategies—linking products to Geographical Indications (e.g. Darjeeling tea, Basmati rice), clean-label processing, ready-to-cook or ready-to-eat formats, and sustainable packaging—further enhance appeal. By combining certification, traceability, and innovative value additions, Indian organic brands can differentiate themselves, attract consumers, and meet both domestic and global market standards.

SUMMARY

Organic farming in India has expanded steadily in production, certified land, and farmer participation, though fluctuations exist. India has one of the world's largest numbers of organic farmers, reflecting its smallholder-dominated structure, while production exceeds four million tonnes. Exports peaked in 2020–21, with cereals, pulses, oilseeds, spices, tea, coffee, fruits, and processed foods catering to both domestic and global markets, mainly the US, EU, and Canada. Government initiatives like PKVY, MOVCDNER, and APEDA have promoted certification and exports, while the organic input industry is growing rapidly. Rising domestic demand, projected to push the market near USD 10 billion by the early 2030s, is driven by health-conscious consumers. Certification systems (NPOP, PGS) and the Jaivik Bharat logo strengthen credibility, while multi-channel distribution, branding, and GI-linked products add value. Challenges include certification costs, fragmented supply chains, mislabelling, and compliance barriers. With stronger policies, R&D, and infrastructure, India's organic sector can become a mainstream pillar of sustainable agriculture.

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Seeding resilience: Agroforestry's journey

from research to climate action

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Agroforestry as a distinct scientific field took root in the 1970s. Initially an emerging concept, it gained serious recognition in the last decade as global organisations such as the IPCC began highlighting its ecological importance. Today, agroforestry enjoys worldwide attention—not only for its ability to boost farm income, but also for its multiple cross-sector benefits, from supporting livestock and pastoralism to strengthening climate resilience in farming systems.

Keywords: Agroforestry systems, Carbon sequestration, GHG emissions

MANY people assume agroforestry is simply the practice of combining agriculture with forestry, but in reality, it is much broader, more systematic, and interdisciplinary. Agroforestry deliberately integrates trees, shrubs, palms, bamboos, and other woody perennials with crops and/or livestock. This integration may occur side by side in space or sequentially over time. The interactions between these components are both ecological and economic, making agroforestry a unique blend of productivity, sustainability, and environmental care. Over time, the technical phrase "woody perennials" has been replaced by the more familiar term "trees," which sometimes led to the misconception that agroforestry is forestry-dominated. In truth, it is a field that draws knowledge from agriculture, forestry, ecology, economics, and social sciences. The FAO even places agroforestry within the category of "Trees Outside Forests" in its Global Forest Resource Assessment.

In India, agroforestry is often confused with related but distinct practices such as farm forestry and social forestry. Farm forestry typically means cultivating trees in blocks on private farmland for timber, fuel, or other products. Social forestry, introduced in India in 1968 by the British forest expert Jack Westoby, focuses on community benefits like providing fuelwood, fodder, and recreation mostly on community or government lands. Agroforestry, however, is different: It is flexible, farmer-centered, and designed to provide both quick economic returns and long-term ecological services.

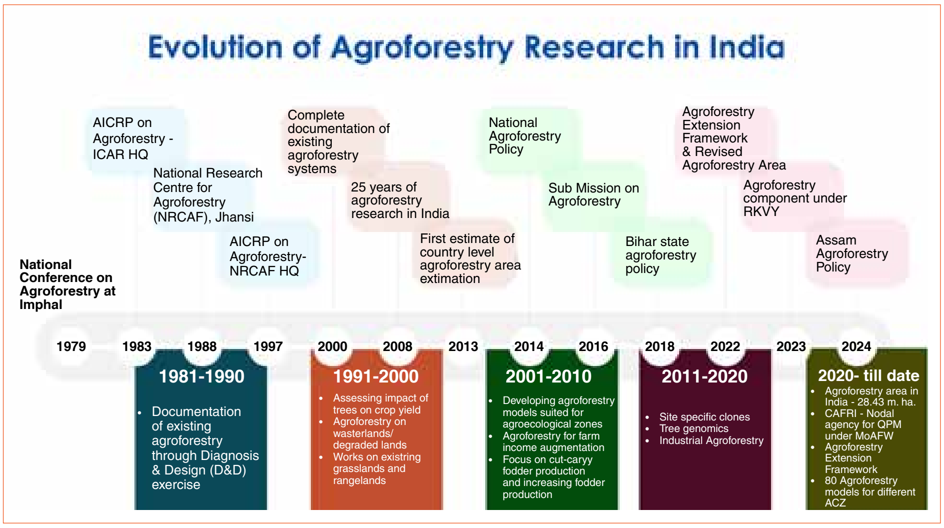
As agroforestry research advanced, another land-use concept began to emerge—Integrated Farming Systems (IFS). Because both approaches promote diversification, they are sometimes compared or even mistaken as similar. Yet, their design and focus differ. Agroforestry integrates trees with crops (sometimes also livestock or fish), whereas IFS links three or more independent enterprises such as crop cultivation, dairy, poultry, or fisheries on the same farm. In IFS, the units work largely on their own, with outputs harvested at different times, and the system often provides quicker cash flow. However, it is more labour-intensive, requires greater technical expertise, and depends heavily on reliable market access.

Agroforestry, in contrast, can be practiced by farmers across scales smallholders to large landowners and requires specialised labour only at certain stages. It also allows innovative combinations like aquaforestry (trees + crops + fisheries) and tree-based beekeeping (trees + crops + apiculture). Its multi-layered vegetation structure promotes vertical use of space, thereby enhancing biomass production and yield efficiency.

From the standpoint of inputs, agroforestry systems generally depend less on synthetic fertilisers, helping reduce costs while lowering environmental damage. IFS, due to its interdependence, is more vulnerable—failure in one enterprise can disrupt others. Agroforestry, by contrast, has relatively independent components that are managed to provide complementary benefits, making it more resilient in the long term.

The roots of agroforestry research

The formal recognition of agroforestry as a scientific field began in 1977, when Canada's International Development Research Centre (IDRC) and the FAO initiated the establishment of the International Centre for Research in Agroforestry (now known as the World Agroforestry Centre). Although its role in temperate



regions was initially debated, India quickly embraced the concept. Following a national seminar organized by ICAR in 1979, the All India Coordinated Research Project on Agroforestry was launched in 1983. The decade from 1977 to 1987 is often described as the formative period for agroforestry worldwide, and during the same years, India firmly institutionalized the discipline. This progression is captured in what can be termed the Agroforestry Research Roadmap.

From research to climate action

What began as farmer-led practices later refined by science has evolved into a central pillar of sustainable agriculture. Agroforestry now contributes multiple benefits—providing food, fodder, fibre, and fuel—while also enhancing soils, improving biodiversity, and capturing carbon. Its unique ability to increase farm productivity and conserve natural resources positions it as a key climate-smart solution, helping build resilience for future generations.

Although trees on farms are not new to India, what has changed in recent decades is the strategic and scientific approach to integrating them. Agroforestry has moved beyond being a traditional practice to being recognized as a climate action tool supported by research, policy, and technology. A landmark step was the adoption of the National Agroforestry Policy, which streamlined farmer participation. Regulatory reforms such as easing timber transit rules for farm-grown trees and the 2017 reclassification of bamboo under the Indian Forest Act (1927) have created new opportunities for cultivation. Initiatives like *Har Med Par Ped* (a tree on every field bund) and funding under the National Mission for Sustainable Agriculture have further incentivized farmers. At the global level, agroforestry has been mainstreamed into climate discussions, with research institutions highlighting its role in resilience building.

Agroforestry and climate change mitigation

The IPCC has acknowledged agroforestry as a land-use strategy with high potential for carbon sequestration. Beyond stabilizing crop yields, it reduces soil erosion, provides fuelwood and construction material, and lessens the dependency on natural forests. In shifting cultivation systems, one hectare of well-managed agroforestry can replace 5–10 hectares of slash-and-burn land. Since systematic research began in the 1970s, its value as a climate strategy has been consistently recognized.

Climate mitigation through trees on farms can be pursued either by conserving existing tree cover or by planting fast-growing, short-rotation species on agricultural lands. Because agroforestry systems combine economic viability with environmental functions, they offer farmers both immediate benefits and long-term adaptation to climate change. Their design—where trees, crops, pastures, and soils interact—maximizes carbon storage and improves microclimates. Additional benefits include maintaining soil fertility, diversifying farm outputs, conserving water, and even strengthening gender equity in rural livelihoods. Two major mitigation mechanisms are involved: Sequestration of CO_2 and reduction of greenhouse gas (GHG) emissions. Evidence from around the world supports these claims. For example:

- In the Peruvian Amazon, nitrous oxide emissions


Mulberry based silvi-pastoral systems


Coconut based horti-pastoral system

Litsea based agri-silvicultural system

Ailanthus based agri-silvicultural

from peach-palm-based agroforestry were three times lower than high-input monocropping systems.

- In Rajasthan, arid agroforestry sequestered 0.26 Mg C/ha/yr at a density of 9.71 trees/ha reducing GHG emissions by 1.42 million tonnes annually.
- In central Alberta, Canada, nitrous oxide emissions under agroforestry were 89% lower compared to conventional croplands.
- In subtropical China, agroforestry systems emitted only 70% of the CO_2 produced by high-input systems, though methane release was slightly higher compared to low-input farms.

Evidence from Indian agroforestry

Studies from Sultanpur, Dinajpur, and Ludhiana districts reported that baseline standing tree biomass ranged from 2.45–2.88 Mg DM/ha, with total tree–crop biomass between 11.14–25.97 Mg DM ha. Soil organic carbon initially recorded at 8.13–9.12 Mg C/ha is projected to rise to 8.63–24.51 Mg C/ha over time. Long-term simulations estimated carbon sequestration potential at 0.111, 0.126, and 0.551 Mg C/ha/yr for Sultanpur, Dinajpur, and Ludhiana, respectively. For the Indo-Gangetic plains as a whole, the potential has been estimated at 36.25 t C/ha.

Potential agroforestry models for India

The ICAR-Central Agroforestry Research Institute (CAFRI) has developed region-specific models suited for different agro-ecological zones. Economic analysis shows that the benefit–cost (B:C) ratios of these models typically range from 1.3–2.5.

Teak based agri-silvicultural system

- ***Melia dubia* based systems:** These are commercially viable and compatible with a wide array of intercrops, including medicinal plants.
- ***Ailanthus excels* based systems:** Six-year-old plantations intercropped with cowpea, cluster bean, and green gram yielded 65.4 kg/ha, 195 kg/ha, and 199 kg/ha, respectively with B:C ratios between 2.4–3.1.
- ***Ardu (Ailanthus) in rainfed conditions:*** Net income varied from ₹55,824–₹76,024/ha, with the highest return recorded when intercropped with green gram. Given its 9–10-year rotation cycle and fodder value, this system outperformed sole cropping.
- ***Khejri based models in Rajasthan:*** These have proven highly resilient and profitable under arid conditions.

In addition, perennial tree-crop combinations are recommended for rehabilitating degraded lands. For example, tamarind-based silvi-horticultural systems have shown promise in Karnataka for land reclamation.

Table 1. Agroforestry models for different agro-ecological regions in India

Agro-ecological regions	Important AFS	Recommended intercrops
Western Himalaya (Cold-arid)	Mulberry based silvi-pastoral systems	Napier-bajra hybrid, Setaria anceps
Western Plain, Kutch and part of Kathiwar peninsula (Hot Arid)	*Melia azedarach* based agri-silvicultural system	Fox-tail millet
Deccan Plateau (400–500 mm rainfall)	*Melia dubia* based agri-silvicultural system	Finger millet and cowpea
Northern Plains and Central highlands including Aravallis	a) *Ailanthus* based agri-silvicultural system (Rainfed condition) b) Shisham based agri-silvicultural system and silvi-pastoral systems c) Aonla based agri-horticultural system	a) Cluster bean, cow pea and green gram b) Wheat, barley, lentil (Rabi) and green gram, black gram, sesame and Napier for Silvo-pastoral system c) Green gram, black gram and seasame (Kharif) and mustard, chickpea (Rabi)

Agro-ecological regions	Important AFS	Recommended intercrops
Central Highlands, Gujarat plains and Kathiwar peninsula	a) *Melia azedarach* based agri-silvicultural system	Soybean (JS-335)
Deccan Plateau (600–1000 mm rainfall)	a) Three tier agroforestry system for paddy growing area b) Teak based agri-silvicultural system c) Sapota based agri-horticultural system (hill zone of Karnataka) d) Tamarind based agri-silvicultural system for degraded lands e) Tamarind based silvi-horticultural systems	a) Paddy (*Kharif*) and black gram, lin seed (Rabi) b) Sorghum and groundnut c) Paddy and maize d) Fodder grass e) Curry leaves
Deccan Plateau (Telangana and Eastern plains)	a) *Terminalia* based agri-silvicultural system b) Tamarind based agri-silvicultural system c) Mango based agri-horticultural system	a) Aloe vera b) Henna c) Sorghum, safflower and cowpea
Eastern ghats, Tamil Nadu uplands, Deccan Plateau	a) *Melia dubia* based agroforestry system c) Coconut based horti-pastoral system	a) Black gram, green gram and red gram b) Cumbu Napier Hybrid
Northern Plains	Poplar based agri-silvicultural system	Mentha, moongbean, maize, sorghum, colocasia (*Kharif*) and wheat, mustard, potato (*Rabi*)
Central Highlands	Bamboo based agri-silvicultural system	Green gram, Black gram, seasame (*Kharif*) and mustard, chickpea and barley (*Rabi*)
Eastern Plateau (Chhattisgarh)	*Gmelina* and *Eucalyptus* based agri-silvi-horticultural system	Mustard, linseed, lentil, okra, bottle gourd
Eastern (Chotta Nagpur) Plateau and Eastern Ghats	Mango based agri-horticultural system	Mango ginger, turmeric and arrow root
Eastern Plain	*Dalbergia sissoo* based agri-silvicultural system	Ginger, turmeric and arrow root
Western Himalayas	*Grewia* based agri-silvicultural system	*Setaria anceps* and fodder
Bengal and Assam plains	a) *Litsea* based agri-silvicultural system b) *Dysoxylum* and Kadamb based agri-silvi-horticultural system c) *Bambusa balcoona* based agri-silvi-horticultural system	a) Bean, groundnut and legume crops b) Rice, mustard, lentil, cabbage, cauliflower, bottlegourd c) Banana, ginger, turmeric
Eastern Himalaya	Agar based agroforestry system	Vegetables, pulses, fruits
North Eastern Hills (Purvanchal)	Alder based agri-silvi-horticultural system	Tea, coffee, maize, rice, ginger, potato, chilli
Eastern coastal plain	a) *Gliricidia sepium* and *Leucaena leucocephala* based silvi-pastoral system b) Guava with *Cenchrus ciliaris* based horti-pastoral system for degraded lands c) *Acacia mangium* based agri-silvicultural system	a) *Stylosanthus scabra* b) *Cenchrus ciliaris* c) Mango ginger, turmeric, and arrow root
Western Ghats and Coastal plains	a) Bamboo based agri-silvicultural system b) Jackfruit and acacia based silvi-horticultural system c) Mulberry and calliandra based silvi-pastoral system	a) Mango ginger, turmeric and arrow root b) Ginger c) Finger millet and proso millet
Islands of Andaman-Nicobar and Lakshadweep	a) Coconut based horti-pastoral system	a) Black pepper and fodder grass

SUMMARY

Over the last fifty years, agroforestry has progressed from being a traditional, farmer-driven practice to a science-backed and policy-supported solution for sustainable agriculture and climate resilience. In India, this transformation has been accelerated through dedicated research, technological innovations, and enabling policies such as the National Agroforestry Policy, simplified tree transit regulations, and state-level agroforestry initiatives. By integrating trees with crops, livestock, and other enterprises, agroforestry enhances farm productivity, diversifies income streams, restores degraded lands, and lowers environmental impacts. Its contribution to climate change mitigation is especially significant, with proven potential for carbon sequestration and reductions in greenhouse gas emissions. The development of region-specific models by ICAR-CAFRI demonstrates agroforestry's adaptability across India's diverse agro-ecological zones, making it relevant and beneficial to farmers of all scales. With both immediate economic gains and long-term ecological benefits, agroforestry represents a future-ready farming pathway. As global and national agendas increasingly align around sustainability and climate action, agroforestry stands out as a practical, scalable, and resilient land-use system that balances livelihood security with environmental stewardship.

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Soil and water conservation practices for achieving land degradation neutrality

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In India, 120.7 Mha of land is degraded, mainly by water and wind erosion and vegetation loss, reducing soil carbon, fertility, and productivity—the key indicators of Land Degradation Neutrality (LDN). Controlling erosion is essential for sustainability and LDN. Agronomic practices such as conservation tillage, cover crops, mulching, broad-bed furrow, ridge and furrow, bench terracing, vegetative barriers, and agroforestry restore soil health and enhance productivity. Geotextiles further protect slopes and riverbanks in high-rainfall regions. Agroforestry also improves fertility through nitrogen fixation, carbon sequestration, and efficient water use. Integrated adoption of these measures is crucial for soil conservation, food security, and achieving LDN.

Keywords: Agroforestry, Cover crops, Conservation agriculture, Residue retention, Soil erosion

UNREGULATED exploitation of natural resources to meet the demands of a growing population, combined with climate change, has intensified land degradation in India. About 120.7 Mha, nearly 36.6% of the country's area, is degraded, with 73.2 Mha affected by water erosion and 12.4 Mha by wind erosion. These processes reduce soil fertility and productivity, causing annual nutrient losses of 5.37–8.40 Mt, deplete about 115 Mt of soil organic carbon, and increase the risks of floods, landslides, and desertification. Globally, soil erosion is recognized as a major threat to food security and ecosystem services. The United Nations Convention to Combat Desertification (UNCCD) defines LDN as a state where land resources remain stable or improve to sustain productivity and ecosystem functions. Monitoring relies on Sustainable Developmental Goal (SDG) indicator 15.3, which includes land cover, productivity, and soil organic carbon. Since erosion directly reduces carbon stocks, it is also recommended as a complementary LDN indicator. In India's agrarian economy, erosion control is critical for food security and resilience to climate change. Agronomic measures such as contour farming, conservation tillage, cover crops, mulching, vegetative barriers, intercropping, agroforestry, and innovative land configurations restore soil functions and support climate-smart agriculture. Strengthening adoption of these low-cost practices offers a sustainable pathway to rehabilitate degraded lands and achieve LDN.

Agronomic soil and water conservation practices

Conservation tillage: Conservation tillage, combined with practices such as soil cover and crop diversity, has emerged as a sustainable option for long-term food production. Conservation tillage practices include zero tillage (ZT), reduced or minimum tillage, mulch tillage, and ridge tillage. These approaches help reduce soil disturbance, limit crop residue loss, moderate soil evaporation, and minimize erosion, while also improving water use efficiency (WUE) compared to conventional tillage. ZT and reduced-till systems are particularly effective in humid and sub-humid regions. In dryland areas, however, tillage plays an important role in conserving soil moisture.

Broad bed furrow: The use of broad bed furrow (BBF) offers multiple benefits in rainfed farming. Raised beds act as an effective drainage tool, reducing waterlogging while enhancing crop yields. BBF conserves soil moisture, improves infiltration, and minimizes runoff and erosion. It provides drainage during heavy rains and retains moisture during dry spells, thereby reducing the impact of extreme weather and supporting higher productivity. The system typically consists of a raised flatbed about 95 cm wide and a shallow furrow around 55 cm wide and 15 cm deep, laid across the slope. Planting soybeans on BBF has shown a 21% increase in yield compared to flatbed planting, with higher net returns.

Ridges and furrows: The formation of ridges and furrows is highly effective for conserving soil moisture and reducing runoff and soil loss, especially in light

Broad-bed and furrow

Ridge and furrow

soils. In medium to deep black soils, furrows are opened 50–60 cm apart across the slope after primary tillage, usually during late June to July. Cultivating crops under the ridge-and-furrow system across the main land slope, with a gradient of 0.2–0.4% on fields having a 1–3% slope, helps conserve more rainwater *in situ*. In vertisols, the ridge-and-furrow method conserved significantly more rainwater and improved crop performance, resulting in 26% higher winter sorghum grain yield and 25% greater WUE compared to flat sowing.

Contour cultivation: Contour cultivation involves carrying out field operations, including sowing, along the contour or across the slope. This creates small barriers that slow down rainwater, reduce runoff, and minimize soil loss. By increasing surface roughness, it promotes ponding in furrows, enhances infiltration, and lowers erosion. Studies have shown that contour farming can reduce annual runoff by about 10%, soil loss by nearly 50%, and water loss by 32%. It also helps retain nutrients like nitrogen and phosphorus more effectively than up- and downslope tillage.

Conservation furrow system: The conservation furrow is a low-cost, *in situ* practice designed for conserving rainwater and soil in rainfed regions with 400–900 mm rainfall and moderate slopes of 1–4%. It is particularly useful in alfisols and similar soils that face crusting and early runoff problems. In this method, furrows are opened 3–5 m apart along the contour or across the slope, either at planting or during intercultural operations using a country plough. These furrows capture runoff water and enhance soil moisture in nearby crop rows, especially during dry spells. Adoption of this system has been shown to improve crop yields by 10–25%.

Compartmental bunding: Compartmental bunding involves dividing fields into small square or rectangular sections to impound rainwater. It is commonly practiced in medium and black soils to store monsoon water in the soil profile for use by *rabi* crops. By allowing more time for rainwater to infiltrate, it wets the soil profile thoroughly, enabling timely sowing of winter crops and improving yields. The recommended compartment size depends on land slope: 6 m × 6 m for up to 1% slope, 4.5 m × 4.5 m for 1–2% slope, and 3 m × 3 m for slopes around 2%. This practice has been shown to increase sorghum yields by 17% and WUE by 13%, over flat sowing.

Cover crops: Cover crops are grown to protect soil

Conservation furrow

Compartmental bunding

Cover crop

Residue retention/mulching

from erosion and nutrient losses through leaching and runoff. They provide soil cover during fallow periods, reducing erosion and suppressing weeds. Leguminous cover crops also fix atmospheric nitrogen, enhancing nutrient cycling and soil fertility. By intercepting rainfall and slowing runoff, cover crops reduce sediment loss and improve soil biological, chemical, and physical properties, including organic carbon content, cation exchange capacity, aggregate stability, and water infiltration.

Residue management/mulching: Residue management or mulching is an essential practice in modern soil and water conservation. It improves water infiltration, retains organic matter, reduces erosion, and helps maintain soil moisture under variable climatic conditions. Applying crop residues such as straw in soybean and wheat systems can increase WUE by 17–23%, while maize–wheat systems under conservation agriculture (permanent beds with crop residue or ZT with residue) can boost water productivity by 30–45% in maize and 16–19% in wheat.

Crop diversification: Crop diversification is a key agronomic strategy for optimizing natural resource use and sustaining agro-ecosystem services. Diversifying crops enhance the resilience of farming systems and ensures better ground cover throughout the year. For example, replacing upland paddy with soybean or groundnut in hilly areas can reduce sediment yield by around 28–30%. Similarly, diversifying continuous wheat with wheat-pea, wheat-barley-pea, or wheat-barley-maize-pea rotations can increase WUE by 8–15%. Rotating wheat with field pea or other low-water-demand, early-maturing crops further improves yield and WUE.

Mechanical soil and water conservation practices

Contour and graded bunding: Field bunding across slopes helps retain runoff, enhance infiltration, and conserve soil moisture. Contour bunds are constructed along contour lines on slopes of 2–6% with annual rainfall below 600 mm. They typically have a height of 50 cm, a cross-sectional area of 1.61 m^2, and a vertical interval of 0.9 m, with horizontal spacing of 50–70 m, while excess runoff is drained through waste weirs. Graded bunds, on the other hand, have a longitudinal slope of 0.2–0.4%, a vertical interval of 0.75 m, and a cross-sectional area of 0.83 m^2, spaced 60–70 m apart, making them suitable for black soils prone to waterlogging. In semi-arid regions, field bunding has been shown to increase crop yields by over 14% and WUE by about 10% due to improved soil moisture.

Bench terracing: Bench terracing is a common soil conservation practice in hilly areas with steep slopes. It transforms steep land into a series of level

Contour bunding

Graded bunding

Bench terracing

Conservation bench terracing

strips supported by risers, reducing slope length and conserving soil and moisture, thereby improving crop productivity. It is generally recommended for slopes of 16–33%, but has been used on slopes up to 50% in regions like the Nilgiris and Himalayas. Bench terraces are classified by terrain and cropping needs: Levelled (table-top) terraces suit medium rainfall and deep, permeable soils, while inward-sloping terraces are ideal for high-rainfall areas and water-sensitive crops like vegetables.

Conservation bench terracing: Conservation bench terracing is practiced in low- to medium-rainfall areas of vertisols with contour or graded bunds. In this system, about 30% of the upstream area near the bund is leveled by cutting around 15 cm of soil and depositing it near the bund, creating flat land for assured crop production even in drought years. The lower one-third of the inter-bunded area is also leveled to spread runoff water over a larger surface. Typically, water-demanding crops are grown in the leveled receiving area, while drought-tolerant crops are sown in the unlevelled donor area. This ensures reliable harvests in drought years and allows for two crops during normal rainfall years, thereby enhancing both cropping intensity and overall productivity.

Conservation ditching: It is also known as inverted contour bunding, developed by ICAR-IISWC, Research Centre, Ballary, Karnataka especially for black soil. Conservation ditching involves creating trapezoidal ditches along the contour or slope to collect and convey excess runoff safely. These ditches reduce soil erosion, improve water infiltration, and help manage excess water in areas prone to runoff. They are particularly useful for crops grown on sloping lands, where uncontrolled water flow can damage soil structure and reduce fertility.

Contour trenching: Contour trenching is a technique in which small trenches are dug along the contour lines of sloping land to capture and store rainwater. These trenches slow down runoff, promote infiltration, and reduce soil erosion. Trenching can be practiced on slopes not exceeding 20%. Trenches are usually 45 cm with a spacing of 10–30 cm between trenches. The captured water increases soil moisture in adjacent crop areas, making it particularly effective in semi-arid regions or areas with shallow soils. Contour trenches are simple and cost-effective, providing immediate benefits in moisture conservation and soil fertility.

Biological soil and water conservation practices

Vegetative barriers*:* Vegetative barriers, also known as live bunds, are an effective, low-cost alternative to physical soil conservation structures. They consist of closely spaced rows of grasses or shrubs planted along the contour to control erosion, reduce runoff, and enhance soil moisture. These barriers also provide biomass for rural communities and can be combined with small bunds on steeper slopes to improve effectiveness. Vetiver, Guinea, and lemon grass are suited to various soils and agro-ecological regions. For example, planting two rows of grass at one-meter vertical intervals on a 2% slope reduced runoff, soil loss, and increased crop yields in maize-wheat systems.

Agroforestry systems: Agroforestry systems integrate trees with crops to enhance soil fertility, improve microclimates, conserve water, and reduce erosion, making them highly effective in rainfed areas. Trees improve soil structure, increase organic carbon,

Contour ditching

Contour trenching

Agri-horticulture system

Silvo-aromatic system

enhance moisture retention, and facilitate nutrient cycling, which helps mitigate drought impacts and improve crop productivity. Hedgerows, such as those with Gliricidia, can reduce runoff by 29% and soil loss by up to 48%, stabilizing slopes and improving soil fertility over time. Additionally, agroforestry contributes significantly to carbon sequestration in both biomass and soil, with potential rates ranging from 0.3 to 15 Mg C/ha/ yr, helping mitigate climate change while enhancing overall land productivity.

Bio-engineering soil and water conservation practice

In non-arable lands, combining agronomic and engineering measures effectively controls soil erosion, and geotextiles play a significant role in this approach. Geotextiles are woven mats made from natural fibers such as jute, coir, or giant cane, used to stabilize slopes, protect riverbanks, and improve soil moisture retention. When placed at regular intervals along slopes, geotextiles reduce runoff, prevent soil loss, and enhance crop productivity. For instance, using geotextiles in rainfed groundnut and maize systems has been shown to increase yields by 36–64%, improve soil organic matter, and reduce runoff by up to 24%.

Table 1. Impact of different soil and water conservation practices on soil carbon, soil properties, runoff, soil loss, and productivity

SWC practices	Location	Crop/Cropping system	Impact
Minimum tillage	Madhya Pradesh	Soybean-Wheat	52% ↓ in soil loss
BBF	Andhra Pradesh	Black gram	Yield ↑ by 12.8%
Ridges and furrows	Tamil Nadu	Potato	30% ↓ in soil loss and 8% ↑ in potato equivalent yield
Contour farming	Telangana	Green gram	Yield ↑ by 45% over up and down cultivation
Compartmental bunding	Uttar Pradesh	Sorghum	Conserved soil moisture by 14.0–30% over farmer's practice
Cover crops	Gujarat	Clusterbean	Soil loss reduced by 73% over fallow.
Residue retention/ mulching	Gujarat	Cowpea + castor intercropping	Reduced runoff by 59.6% respectively over farmer practice.
Contour bunding	Rajasthan	Mustard	Economic and biological yield ↑ by 14.4% and 15.3% over no bunding
Bench terracing	Gujarat	Sapota and cowpea	↓ runoff by 34% ↓ soil loss by 25%
Conservation bench terraces	Uttarakhand	Rice, maize, cowpea	↓ runoff by 80% ↓ soil loss by 88%
Contour trenching	Rajasthan	Aonla + Anjan grass + bamboo	↓ runoff by 86% ↓ soil loss by 125%
Vegetative barrier	Gujarat	Pigeon pea	↓ runoff by 20% ↓ soil loss by 51%
Silvo-aromatic system	Gujarat	Lemon grass + *Meliadubia*	↑ total CO2-sequestration by 255 % over sole Melia.
Geotextiles	West Bengal	Groundnut	Crop yield and SOC ↑ by 64.2% and 53%, respectively.

SUMMARY

Land degradation affects 120.7 Mha in India, mainly from water and wind erosion, leading to vegetation loss, and soil fertility decline. Controlling erosion is vital for achieving LDN and sustaining productivity. Agronomic measures (e.g. conservation tillage, broad-bed furrow, ridges and furrows, contour farming, cover crops, mulching, diversification) improve infiltration, conserve moisture, and enrich soils. Mechanical interventions (basin listing, subsoiling, bunding, terracing, ditching, trenching) reduce runoff and stabilize slopes. Biological measures (vegetative barriers, agroforestry) curb erosion, recycle nutrients, and sequester carbon. Bio-engineering solutions like geotextiles reinforce slopes, protect riverbanks, and enhance yields in erosion-prone areas. Integrated adoption of these practices ensures sustainable land management, strengthens food security, and advances India's LDN goals.

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Smart nutrient management practices

for sustainable crop production

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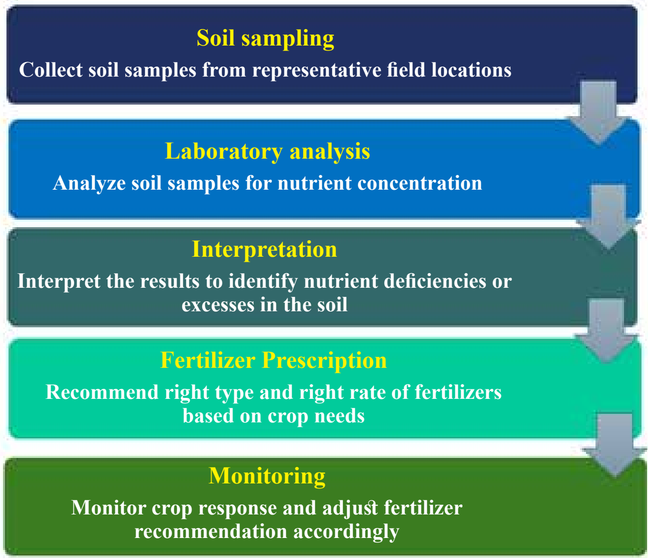
Global food security faces pressure from rising population, climate change, and shrinking natural resources. In India, the second-largest fertilizer consumer after China, fertilizers contribute ~40–50% of yield gains, making nutrient management essential. Yet, inefficient use results in poor utilization efficiencies i.e. 30–50% for nitrogen, 15–20% for phosphorus, 50–80% for potassium, and <5% for micronutrients—leading to widespread deficiencies and declining nutrient use efficiency (NUE), especially in cereals like rice, wheat, and maize. To address this, Smart Nutrient Management (SNM) practices are vital. Based on the 4R nutrient Stewardship principle, SNM integrates Soil-Test Crop Response (STCR), Integrated Plant Nutrient Supply (IPNS), and Site-Specific Nutrient Management (SSNM). Tools like SPAD meters, leaf colour charts, and GreenSeeker sensors guide in-season decisions, while organic residue recycling, microbial inputs, and crop residue management enhance soil health. Innovations like nano-fertilizers, green fertilizers, digital soil mapping, and IoT-enabled systems enable precision nutrient delivery. Together, SNM enhances productivity, improves NUE, lowers costs, and reduces environmental impacts.

Keywords: Digital soil mapping, Green fertilizer technology, Site-specific nutrient management

SOIL health underpins sustainable agriculture, shaping productivity, food quality, and ecosystem resilience. Yet, soils globally face severe threats from erosion, nutrient depletion, salinization, compaction, organic matter loss, and declining microbiomes essential for nutrient cycling. Intensive agriculture and contamination by heavy metals, pollutants, and excess nutrients further compromise food safety and groundwater. Blanket fertilizer use has proven inefficient, with low utilization efficiencies—nitrogen (30–50%), phosphorus (15–20%), potassium (50–80%), and micronutrients (<5%)—leading to nutrient losses, environmental degradation, and greenhouse gas emissions. Smart Nutrient Management (SNM), rooted in the 4R principle, offers solutions by aligning inputs with soil and crop demand. Approaches like STCR, IPNS, and SSNM optimize nutrient delivery, supported by tools such as SPAD meters, LCC, and GreenSeeker sensors for real-time adjustments. Integrating organic residues, microbial inoculants, indigenous minerals, and residue recycling restores soil vitality. Emerging innovations such as nano-fertilizers, climate-smart fertilizers, DSM, and IoT systems further improve efficiency. Collectively, SNM sustains soil health, boosts productivity, and strengthens climate-resilient food systems.

Approaches of smart nutrient management (SNM) practices

Soil-test based fertilizer recommendation (STCR): STCR is widely regarded as the cornerstone of balanced and efficient nutrient management in modern agriculture. It ensures that nutrient inputs are aligned with both the inherent nutrient-supplying capacity of the soil and the precise requirements of the crop. The process begins with the systematic collection of representative soil samples, which is a critical step to capture the true fertility status of the field. Thereafter, soil samples are subjected to laboratory analysis to assess key soil properties including soil texture, pH, electrical conductivity, organic carbon, and the availability of major nutrients (N, P, K), secondary nutrients (Ca, Mg, S), as well as micronutrients (Zn, Fe, Cu, Mn, B, etc.). Based on soil analysis, nutrient recommendations are developed through correlation and calibration that link



Soil-test based fertilizer recommendation

Site-Specific Nutrient Management (SSNM)

soil test values with crop response. Such an approach not only enhances NUE and crop yield but also reduce nutrient losses and production costs, and contributes to environmental sustainability by preventing over or under use of fertilizers.

Integrated plant nutrient supply system (IPNS): IPNS emphasizes the balanced and combined use of inorganic fertilizers with organic amendments such as FYM, compost, vermicompost, crop residues, green manures, and biofertilizers, along with the inclusion of legumes in cropping systems. The primary objectives of IPNS are to reduce dependence on chemical fertilizers, restore and maintain soil organic matter, improve nutrient-use efficiency, and sustain soil quality in terms of its physical, chemical, and biological properties. By ensuring a steady supply of macro- and micronutrients, IPNS supports higher productivity, reduces input costs, and promotes environmentally sustainable farming. Long-term studies on vertisols have shown that such integrated practices enhance soil organic carbon, improve nutrient availability, while also contributing to carbon sequestration improving the energy use efficiency while reducing carbon footprint. Its adaptability to local conditions makes it a practical and eco-friendly strategy for long-term agricultural sustainability.

Site-specific nutrient management (SSNM): The SSNM is a nutrient management practice that aims to provide crops with nutrients following the 4R nutrient stewardship idea: The right nutrient source, at the right rate, at the right time, and in the right place, based on site-specific conditions. It targets field level variability in native nutrient (NPK) supply, temporal variability in plant N status occurring within a growing season and medium-term changes in soil P and K from actual nutrient balance. There are three basic approaches for SSNM such as 1) Nutrient omission plot technique: Site-specific nutrient (N, P, K) recommendations can be developed using the nutrient omission plot technique, which quantifies the indigenous nutrient supply from the soil. This approach helps determine the actual fertilizer requirement for achieving target yields under specific site conditions. 2) Nutrient Expert/Decision-Support tools: Use of models, algorithms, or digital tools (e.g. Nutrient Expert for maize and rice) to estimate crop nutrient requirements based on site conditions, yield targets, and nutrient balances. 3) Real-Time Nutrient Management (RTNM): Involves in-season diagnosis using tools like SPAD chlorophyll meter, Leaf Colour Chart (LCC), or sensors to apply nutrients especially nitrogen-based on crop demand and growth stage.

Chlorophyll-meter (SPAD-meter): The chlorophyll meter (SPAD meter) is a handheld diagnostic tool that estimates relative leaf chlorophyll content, which is closely associated with leaf nitrogen status. It provides a rapid, non-destructive, and real-time assessment of crop N nutrition, thereby helping in site-specific and in-season nitrogen management. Studies across a range of crops including maize, wheat, cotton, and apple have

Chlorophyll-meter (SPAD-meter)

Leaf colour chart

shown a strong relationship between SPAD readings and crop nitrogen status. Basically, the SPAD reading reflects the chlorophyll content in leaves, which in turn correlates with plant nitrogen concentration and yield potential. Thus, by using the SPAD meter, farmers can apply nitrogen at the right time and in the right amount, avoiding wastage and reducing costs while improving productivity. Hence, the chlorophyll meter is an effective tool for guiding balanced nitrogen application and improving crop productivity while minimizing losses to the environment.

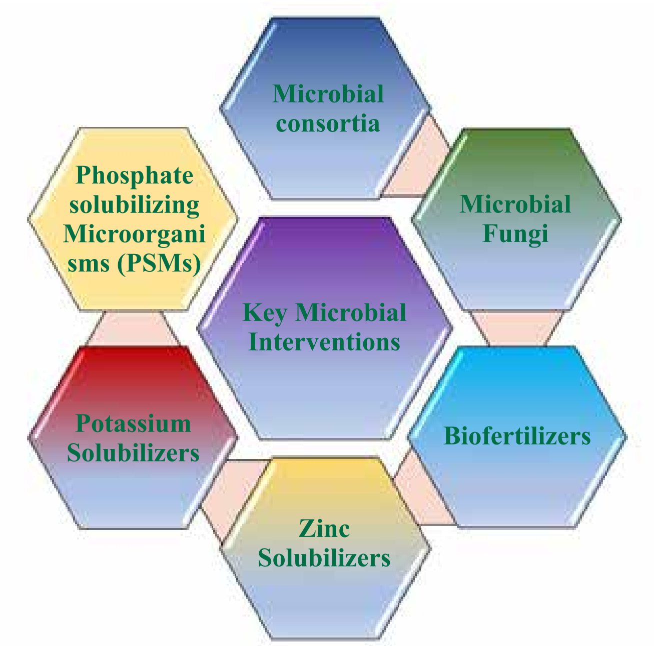
Leaf colour chart (LCC): LCC is easy to use, low cost and helps farmers give the right amount of nitrogen fertilizer to many crops. LCC is a plastic, ruler-shaped strip containing four or more panels that range in colour from yellowish green to dark green. The standardized LCC is five inches long, made of high-quality plastic, and consists of six colour shades from yellowish green to dark green. The colour strips are fabricated with veins resembling crop leaves. By matching the colour of the leaf to the colour on the LCC, farmers can decide the proper time and amount of N fertilizer for application. In maize, the LCC helps decide the right time for N application. Every 7 to 10 days from the time of sowing until tasseling, compare the topmost fully opened leaf with the LCC.

The middle part of the leaf is placed on the LCC and compared with the colour panel. If most leaves are lighter than shade 4, apply nitrogen; if equal to or darker, no fertilizer is needed. Regular use ensures need-based N application, saving fertilizer and improving yield.

GreenSeeker™ sensor technology: The Green Seeker is an active optical sensor designed to assess in-season crop nitrogen (N) status and guide site-specific N management. This instrument is used to measure Normalized Difference Vegetation Index (NDVI) of plants and the value of NDVI is correlated with the N content in the plant. The sensor operates by emitting red and near-infrared light onto the crop canopy and measuring the reflectance to calculate the NDVI. Higher NDVI values indicate greener, healthier, and N-sufficient crops; lower values indicate nitrogen stress. GreenSeeker-based measurements allow for real-time estimation of crop N demand, thereby enabling precise, need-based fertilizer application. A small plot in the field is fertilized with a non-limiting dose of nitrogen (N-rich strip). The GreenSeeker sensor measures the NDVI of this N-rich strip, which is then used as a reference to compare the nitrogen status of the crop in the rest of the farmer's field. For optimal performance, the instrument is operated by walking across the field while holding the sensor 24–48 inches (60–120 cm) above the crop canopy. NDVI values from the field are compared with those from the N-rich strip, and calibration models are then used to convert NDVI differences into site-specific nitrogen requirements (kg N/ha).

Microbial interventions: Sustainable crop production requires nutrient management strategies that not only enhance yield but also protect soil health and reduce environmental degradation. Chemical

GreenSeeker sensor



Key microbial interventions

fertilizers have led to declining soil fertility, nutrient imbalances, and other environmental risks. So, microbial interventions within SNM practices offers an innovative pathway to ensure balanced nutrient supply, improved nutrient-use efficiency, and long-term sustainability. Microorganisms play a pivotal role in mobilizing, fixing, and transforming nutrients in the soil–plant system. Key microbial interventions include:

- **Biofertilizers:** *Rhizobia*, *Azotobacter*, and *Azospirillum* fix atmospheric nitrogen and reduce dependence on synthetic N-fertilizers.
- **Phosphate-solubilizing microorganisms (PSMs):** *Bacillus* and *Pseudomonas* species release organic acids that solubilize insoluble phosphates, enhancing P availability.
- **Potassium and zinc solubilizers:** Certain bacteria and fungi mobilize micronutrients, ensuring balanced nutrition.
- **Mycorrhizal fungi:** Improve phosphorus uptake, micronutrient acquisition, and water-use efficiency through extended hyphal networks.
- **Microbial consortia:** Synergistic combinations of bacteria and fungi provide multiple nutrient benefits and resilience under variable field conditions.

In situ management of crop residue: Crop residue management is crucial for sustainable farming, as burning residues leads to pollution, nutrient loss, and soil degradation. *In situ* approaches like incorporation, mulching, and residue retention improve soil health, organic matter, microbial activity, and water conservation, while releasing nutrients (N, P, K, micronutrients) to reduce fertilizer dependence. Conservation tillage with residue retention enhances SOC, prevents erosion, and sustains productivity compared to conventional tillage. Zero tillage with stubble retention further preserves soil aggregates and long-term SOM. Integrating residue management with site-specific nutrient management and precision tools ensures balanced nutrient supply, reduces losses, enhances NUE, and supports resilient, resource-efficient crop production systems.

Climate smart green fertilizer: Green intelligent fertilizers are the latest emerging technology in which high-quality fertilizers were produced based on the principles of synchronizing plant nutrition based on crop demand, kind of soil and prevailing environmental situations. It relies on use of artificial intelligence for managing the specific supply-demand based upon requirement, enhancing the root-fertilizer interaction by intensifying crop biological potential, developing new advanced green manufacturing technology which can stimulate the rhizosphere effects in the root zone on crop plants and enhancing the utilization of mineral resources contained in raw materials. Green intelligent fertilizers not only increase yield and improving quality of food, but also serve as an important entry point for integrating the fertilizer industry and agricultural chain via green transformation of the fertilizer production.

Nanotechnology: Nano size fertilizer materials have great advantage for its application to agricultural crops. Reducing the size of fertilizer materials aid to enhance nutrient uptake by crop plants and reducing the loss of fertilizer material from soils. Due to higher reactivity of nano fertilizer material they form complexes with the different material in soil and plant which can also help in controlled release of plant nutrients. Further coating of nano-fertilizers with materials like polymer also act as barrier for controlled release of plant nutrients into the soil. The other liquid nano-fertilizers such as Nano-emulsion is also advantageous in the sense that it allows more nutrients in a single droplet. The use of IT based nano sensors are also recently emerged technology for effective fertilizer management for real-time sensing and managing the fertilizer release from the nano based controlled release fertilizer materials.

Digital soil mapping for parcel specific fertilizer recommendation: Digital Soil Mapping (DSM) is the recently introduced concept for fast mapping of soil resources and its attributes. The DSM is basically the approach of creation of soil information systems by using the mathematical models by considering the interaction between soil attributes and related environmental factors (covariates). It is very useful technique for the prediction of key soil attributes such as soil depth, pH, organic carbon, textural fractions, and soil moisture. Among the different models recently studied, Regression Kriging has been accepted method for mapping of soil nutrients with fairly good accuracy.

IoT-enabled nutrient delivery systems: The Internet of Things (IoT)-enabled nutrient delivery systems represent a modern approach to precision agriculture. In this approach, sensor-based, automated, controlled, and optimized fertilizers are applied by using smart devices. It is a combination of standard protocols of agronomy, automation, and data science that are offering real-time nutrient management, particularly in controlled environments. Application of IoT-based technologies such as sensors, actuators, cloud platforms, and analytics, which are able to monitor and regulate the nutrient delivery based on real-time crop and weather data. In this system, continuously monitor soil moisture, temperature, soil pH, and nutrient concentration in real time and accordingly regulate the type and amount of nutrients applied to crops. Hence, farmers can make informed decisions and remotely control irrigation and fertilizers by connecting sensor data with cloud-based analytics and mobile applications. Applying IoT-based fertilizers not only improves the NUE and crop yield but also reduces input, minimizes the environmental losses, and ensures sustainable crop production.

SUMMARY

Global food security faces pressures from population growth, climate change, and resource decline, while in India, low NUE, soil degradation, and shrinking farmland exacerbate concerns. Sustainable Nutrient Management (SNM) aligns with SDGs by promoting cost-effective, resource-efficient practices. Based on 4R stewardship, SNM integrates STCR, IPNS, and SSNM, supported by tools like SPAD meters, LCC, and GreenSeeker for real-time adjustments. It emphasizes organic residue valorization, microbial inoculants, and residue management to restore soil health. Emerging innovations such as green fertilizers, nano-fertilizers, DSM, and IoT-enabled systems enable precision nutrient delivery. Together, SNM strategies enhance yields, improve NUE, reduce losses, and sustain productivity.

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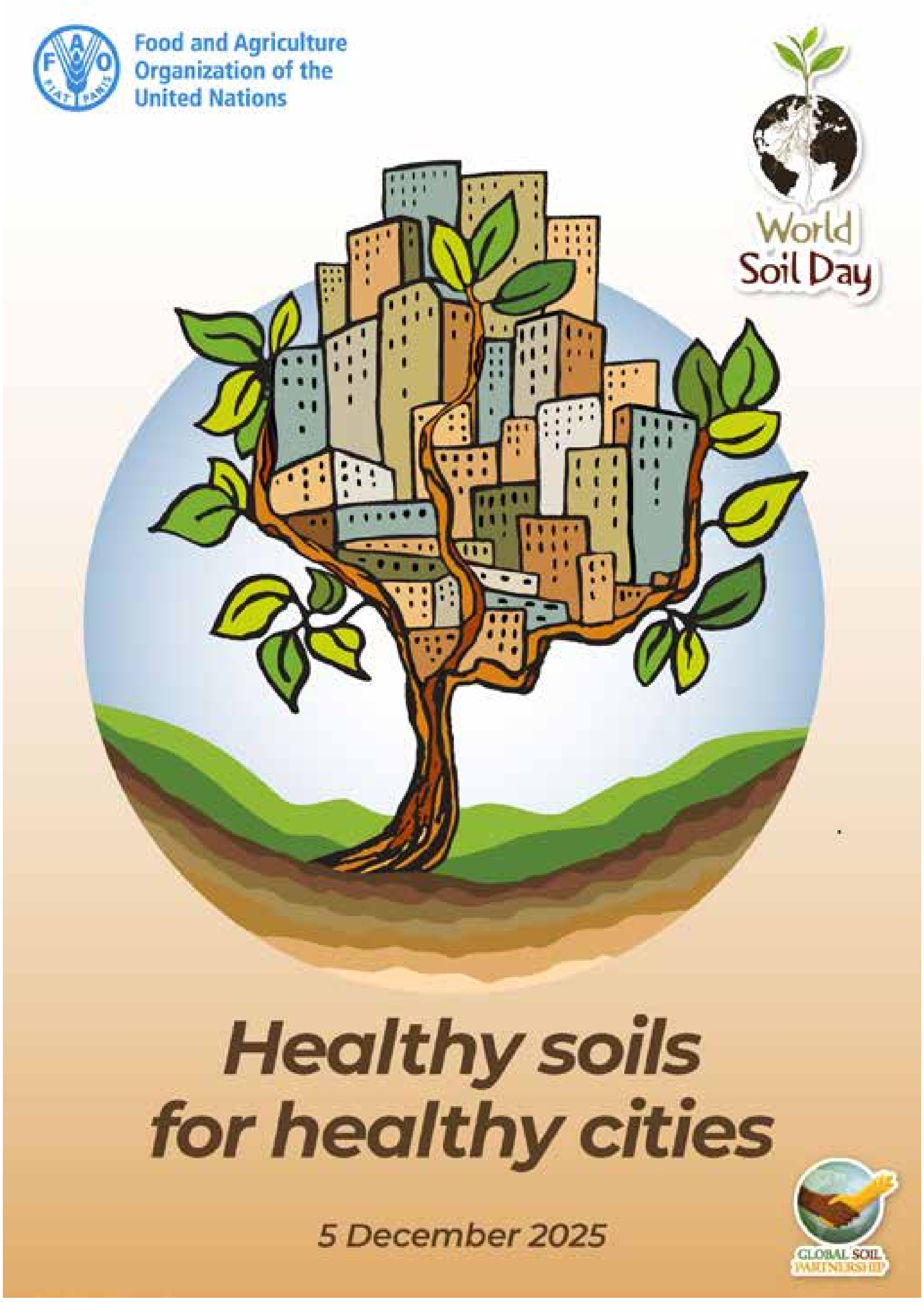

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Zinc application boosts rice productivity in Tarai region of Uttarakhand

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Zinc is an essential micronutrient vital for plant growth, structural integrity of membranes, protein synthesis, and gene expression. Though required in small amounts, its deficiency severely limits crop productivity. In the Tarai region of Uttarakhand, rice yields improved significantly with Zn application, especially under balanced nutrient use. Treatments with 100% NPK+Zn and 100% NPK+FYM increased yields by 45% and 56% over 100% NPK, respectively, highlighting Zn as the most limiting factor. Integrated nutrient management sustained Zn availability over time. Thus, incorporating Zn in fertilizer schedules is critical for enhancing and maintaining rice productivity.

Keywords: Fertilizer, Mollisols, Plant nutrition, Rice, Uttarakhand, Zinc

RICE (*Oryza sativa* L.) remains the dietary backbone for more than 65% of India's population, shaping national food security, rural livelihoods, and the agricultural economy. In 2024–25, rice was cultivated on 51.42 million hectares, producing 149.07 million tonnes with an average productivity of 2900 kg/ha (DES 2025). Despite being a major rice-producing state, Uttarakhand records comparatively modest productivity, with rice covering ~4.5 lakh ha, producing ~5 lakh tonnes, and yielding ~2.5 t/ha. The lower yield levels, particularly in the fertile Tarai belt, underscore the significance of nutrient-related constraints in the production system. Among micronutrients, zinc (Zn) has emerged as a crucial limiting factor for rice productivity in this region. Zinc, though required in minute quantities, plays indispensable roles in enzyme activation, auxin synthesis, chlorophyll formation, and regulation of protein and nucleic acid metabolism. Its deficiency adversely impacts tillering, leaf area expansion, pollen viability, and ultimately grain yield. National Soil Fertility surveys revealed that 40–50% of Indian soils are zinc-deficient, with higher prevalence in intensively cultivated, sandy loam, calcareous, and alkaline soils.

Field studies in the Tarai region demonstrated that inclusion of Zn with balanced nutrient schedules significantly enhances rice yield. While 100% NPK fertilization improves productivity, addition of Zn (100% NPK + Zn) and integrated nutrient management (100% NPK + FYM) led to yield gains of 45% and 56%, respectively, over 100% NPK alone. This yield advantage is attributable to the fact that under control conditions, soil Zn levels often drop below the critical threshold, making it the most limiting nutrient for rice growth. Long-term experiments also highlight that Zn application not only corrects deficiency but also improves soil Zn reserves, while integrated nutrient management sustains its availability over years. Thus, strategic Zn fertilization, either through direct Zn amendments or in combination with organic manures, is pivotal to sustaining rice productivity in the Tarai region of Uttarakhand. Adoption of balanced and integrated nutrient management practices can help overcome widespread Zn deficiency, improve nutrient use efficiency, and ensure resilience of rice-based systems in the long run.

Role of Zinc (Zn)

The Zn ions have both beneficial and toxic effects on plant cells. It is inevitable in several plant metabolic processes like activation of carbonic anhydrase, protein synthesis, RNA polymerases, superoxide dismutase, alcohol dehydrogenase, lipid and nucleic acid, carbohydrate, metabolism. Also, as the Zn ions are integral parts of Zn finger family of transcription factors, thus, controls cell proliferation and differentiation. Besides these, Zn also plays important role in development and function of chloroplast. Thus, there is need of Zn by the cells for maintaining Zn homeostasis. The synthesis of chlorophyll in plants as well as reduction in growth and tolerance to stress happens during Zn deficiency. Zn is an important component of various enzymes that are responsible for driving many metabolic reactions in all crops. Growth and development would stop if specific enzymes were not present in plant tissue. Carbohydrate, protein, and chlorophyll formation is significantly reduced in Zn deficient plants. Therefore, a constant and continuous supply of Zn is needed for optimum growth and yield of plant.

Identification of Zn deficiency

Zn deficiency in India was first reported by Y.L. Nene in 1966 in paddy fields at Pantnagar, Uttarakhand. Dr. Nene is recognized as a pioneer in identifying Zn deficiency and developing strategies for its management. Globally, Zn deficiency in rice is known by various names: Khaira in India, Akagare Type II in Japan, Taya-Taya/Apulapaya in the Philippines, Hadda in Pakistan, and suffocating disease in Taiwan. Since its discovery, Zn deficiency has been acknowledged as a major nutritional constraint in rice-growing regions of Japan, USA, Brazil, and the Philippines. The total Zn content in soils depends on factors such as parent rock, weathering, organic matter, texture, and pH, with typical values ranging from 10–300 mg/kg (mean 50 mg/kg). Soils derived from basic rocks like basalt are richer in Zn, whereas those from acidic rocks such as granite and gneiss have lower Zn content. Light-textured soils generally have lower Zn than heavier soils. In rice, Zn deficiency impairs normal growth, with symptoms appearing within the first two to three weeks of the growing season. Early signs include yellowing of lower leaves, which progresses to bronze or brown colouration with a rusty appearance. These symptoms, commonly referred to as Khaira, usually appear on young or middle-aged leaves and should be confirmed through plant tissue analysis to distinguish from sunburn damage.

The main visible symptoms are (i) Leaf chlorosis occurs in which leaf colour changes from the normal green to pale green or yellow due to the reduced amount of chlorophyll in the leaf or oxidation of chlorophyll (ii) Necrotic spots on leaves occurs in areas of chlorosis due to death of plant tissue (iii) Bronzing of leaves reflects the development of reddish-brown spots/ lesions on leaves, and it is very typical in rice plants (iv) Rosetting of leaves occurs and consequently, the leaves close together in a cluster instead of being spread out between nodes in a healthy fruit trees (v) Stunting of plants as a result of reduced stem elongation and (vi) Dwarf leaves that is also called "little leaf". The malformed leaves are noticeably narrow and/or have wavy edges instead of straight edges.

Zinc deficiency in soils is directly linked to widespread human malnutrition, making its management crucial for food and nutritional security. Application of Zn to soil and crops offers a simple and effective approach to mitigate this deficiency. Although most crops tolerate high Zn without toxicity, cereals are sensitive, showing stunted growth, brown leaf spots, poor establishment, empty grains, delayed maturity, and yield loss. Deficiency symptoms often resemble S or Fe deficiency. Zn deficiency occurs in neutral to calcareous, sandy, saline–sodic, peat, highly weathered, and intensively cropped soils, especially under continuous flooding or high P and Si status.

Factors affecting Zn availability

Mollisols are among the most fertile soils, widely valued for their deep profiles, dark colour, and high organic matter content. Their excellent nutrient-holding capacity makes them highly productive for agriculture. The organic matter in mollisols not only enriches soil fertility but also influences Zn dynamics by serving as both a source and a chelating agent, thereby enhancing Zn availability for plant uptake. With a near-neutral to slightly acidic pH (around 6–7), mollisols generally

Symptoms of Zn deficiency in rice in LTFE in mollisols (Pantnagar, Uttarakhand) promote optimal Zn solubility and uptake. However, despite these advantages, Zn deficiencies may still occur in crops with high Zn demand or under intensive cultivation. In such cases, the application of Zn-containing fertilizers becomes necessary to maintain crop growth and yield. Sustainable practices such as crop rotation, cover cropping, and reduced tillage help preserve organic matter, ensuring long-term nutrient supply including Zn. Regular soil testing is therefore essential to monitor Zn status and guide appropriate nutrient management strategies, preventing hidden deficiencies in these otherwise fertile soils.

Impact of long-term Zn application on rice productivity

It has been observed that application of Zn in even imbalanced nutrient use found to be beneficial as in case of 100% N, 100% NP and 50% NPK. The balanced nutrient doses are performing well over the years. The 100% NPK+FYM gave maximum yield magnitude of 232% over control. The yield advantage due to 100% NPK+Zn and 100% NPK+FYM found to be at 45 and 56% over 100% NPK, respectively. It is because the soil status of Zn in control (0.57 mg/kg) has drastically gone down below critical level (0.57 mg/kg)and Zn found to be most limiting factor for rice yield as per Liebig's Law of Minimum. However whenever Zn is applied, the Zn status in soil is gradually enhanced and in INM, (100% NPK+FYM) it has been sustained very well. Thus as a result, use of Zn in fertilizer schedule plays a crucial role in enhancing and sustaining the rice productivity. Therefore, it is equally important to have an effective Zn management strategy to improve crop productivity and farm income.

Table 1. Impact of long-term manuring and fertilizer application on yield of rice and available Zn content in soil at Pantnagar (Mollisols)

Year	Control	100% N+Zn	100% NP+Zn	50% NPK+Zn	100% NPK	150% NPK	100% NPK + Zn	100% NPK + FYM	CD (0.05)
	Yield (q/ha)								
2020–21	17.00	34.20	42.00	33.80	34.20	33.23	48.80	53.12	2.01
2021–22	16.79	32.83	42.19	32.75	34.44	33.57	49.38	53.33	2.04
2022–23	15.42	32.76	42.45	33.32	33.10	33.24	48.25	51.68	2.11
2023–24	15.16	32.45	42.25	32.80	32.75	33.15	48.05	51.22	2.25
2024–25	14.12	31.24	42.18	32.04	32.45	32.84	47.65	51.46	-
Mean	15.70	32.70	42.21	32.94	33.39	33.21	48.43	52.16	2.10
Increase over control (%)	-	108.28	168.91	109.85	112.69	111.53	208.49	232.28	
	Available Zn (mg/kg) in soil								
2023–24	0.52	1.55	1.78	1.88	0.79	0.64	1.87	1.23	0.71

* Initial Zn content in soil = 2.7mg/kg; Critical level of available zinc in soil=0.6 mg/kg

Impact of S, Zn and FYM on rice yield under superimposition

In mollisols of Pantnagar, rice showed a significantly higher response to sulphur (S), zinc (Zn), and farmyard manure (FYM) under superimposed nutrient treatments. The application of 100% and 150% NPK in combination with S, Zn, and FYM resulted in maximum grain yield compared to treatments without S and Zn. Notably, sulphur application through S-containing fertilizers, such as single superphosphate (SSP), produced a marked positive effect. Zinc supplementation was critical, as treatments lacking Zn fertilizers exhibited Khaira disease, indicating its role in both yield enhancement and disease mitigation. Rice exhibited strong responses to nitrogen (N), S, Zn, and FYM, whereas responses to phosphorus (P) and potassium (K) were comparatively lower under superimposed treatments. Statistically, S and Zn applications showed at par response in 100% and 150% NPK treatments. Overall, the combined application of S, Zn, and FYM with NPK significantly enhanced rice productivity and crop health, emphasizing the importance of balanced nutrient management for achieving higher yields in Pantnagar Mollisols.

Efficiency of Zn in rice

The estimates on agronomic efficiency for individual nutrients i.e. N, P, K, and Zn was done for mollisols of Pantnagar. Upon application of unit amount of nutrient i.e. P application (36 kg grain/kg P)and Zn application (30 kg grain/kg Zn) recorded highest response compared to N and K. The study clearly depicted the beneficial effect of zinc on growth and yield of rice in this tarai areas as indicated through agronomic efficiency.

Strategies for mitigation of Zinc deficiency

The addition of Zn to starter fertilizer is the most economical and effective approach to correct Zn deficiency, ensuring nutrient availability during the year it is required. When starter fertilizers are not feasible, Zn should be applied through broadcasting and incorporation before planting. Soil application of Zn compounds remains the most common method, while foliar sprays are generally reserved for high-value crops such as fruits, vegetables, and grapes, as well as for field crops showing visible deficiency. Other options include seed treatment and root dipping of seedlings, particularly in rice, where dipping roots in 2–4% ZnO suspension

150% NPK+S+Zn

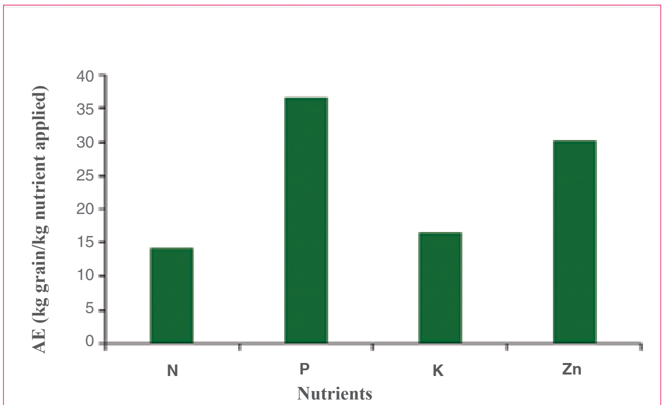
150% NPK+S+Zn+FYM

Impact of superimposition of Zn and S (in 150% NPK) on growth and yield of rice at Pantnagar

Table 2. Rice yields (q/ha) and magnitude of increase with application of S, Zn and FYM under superimposed treatments (2019–2024)

Treatment	2019–20	2020–21	2021–22	2022–23	2023–24	Pooled Mean	Increase in yield over control (%)	Increase due to application of nutrient
100% NPK								
-S	32.15	35.15	36.15	36.25	36.10	35.16		
+S	36.39	38.25	37.25	36.5	37.25	37.13	5.60	S
-S+Zn	39.23	47.23	45.23	44.8	46.05	44.51	26.59	Zn
+S+Zn	44.43	55.53	56.00	52.85	56.35	53.03	50.82	S and Zn
+S+Zn+FYM	50.52	56.52	55.52	53.92	55.45	54.39	54.69	S, Zn and FYM
CD (0.05)	1.32	2.16	3.01	2.16	2.81	-		
150% NPK								
-S	41.15	42.15	40.15	41.30	40.70	41.09		
+S	42.39	43.25	43.25	45.50	45.10	43.90	6.84	S
-S+Zn	45.23	48.23	46.23	46.48	47.15	46.66	13.56	Zn
+S+Zn	54.43	62.53	62.34	62.45	61.10	60.57	47.41	S and Zn
+S+Zn+FYM	57.00	67.52	65.52	66.24	65.25	64.31	56.51	S, Zn and FYM
CD (0.05)	2.23	2.34	2.16	2.45	3.10	-		

before transplanting is widely practiced. Fertigation has emerged as a modern technique for applying Zn fertilizers with NPK through irrigation water, providing uniform distribution, higher efficiency, and reduced risk of plant damage, especially in arid and semi-arid areas. Among commonly used Zn fertilizers, zinc sulphate monohydrate (36% Zn), zinc sulphate heptahydrate (22% Zn), zinc oxysulphate (20–50% Zn), basic zinc sulphate (55% Zn), ammoniated zinc sulphate (10% Zn), and zinc oxide (50–80% Zn) are widely adopted. Zn application rates of 10–25 kg $ZnSO_4$/ha are effective, with residual effects lasting 2–5 crop seasons, except in alkaline soils where annual application is necessary.



Agronomic efficiency (AE) for zinc in rice in mollisols of Pantnagar, Uttarakhand

SUMMARY

To address Zn deficiency in mollisols, several strategies are recommended. Regular soil testing is essential to monitor Zn levels and guide corrective measures. Zinc fertilization, using sources like zinc sulphate or chelates, helps alleviate deficiency, while foliar application ensures quick plant response. pH management around 6–7 improves Zn availability, though drastic pH adjustment is difficult. Crop rotation prevents continuous cultivation of Zn-sensitive crops, reducing deficiency risks. Additionally, optimizing phosphorus fertilization is important, as excess P can limit Zn uptake. Research indicates that most Zn sources, except granular ZnO, are equally effective in enhancing crop productivity and sustaining soil fertility.

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Water smart irrigation technologies and management practices for ensuring food security

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Water use efficient techniques assume significance in agricultural sector of India in the background of diminishing surface and groundwater resources and climate induced natural disasters. Hence, we need to ensure favourable water regime in the rhizosphere zone of plants through precision water management. There is a need to implement water smart irrigation technologies like micro irrigation, solar enabled automated irrigation, etc. to utilize the available water resources in judicious manner thereby ensuring food security.

Keywords: Automated irrigation, Food security, Water smart irrigation

WATER is fundamental to agriculture and underpins global food security without it, crops and livestock cannot survive, and farming operations would grind to a halt. Yet, the rapidly rising demand for both food and animal feed spurred by population growth and shifts in diet is stretching this precious resource to its limits. Compounding the situation are climate change effects: Erratic rainfall, recurring droughts, and hotter conditions undermine both the supply and quality of water available for farming. These pressures threaten crop yields, push up production costs, exacerbate food insecurity, and jeopardize the livelihoods of many whose survival depends on agriculture. Without urgent change, the overuse of groundwater especially in areas lacking reliable surface water could erode the basis of sustainable agricultural systems globally.

At this critical stage, agriculture must embrace "water-smart" solutions that optimize how water is managed and applied. These approaches involve advanced technologies, resource-saving practices, and supportive policies that improve efficiency while safeguarding future supplies. We also need to focus on precision irrigation system which ensures the application of optimum amount of water to the plant at the right time and in the right manner. It also addresses the heterogeneity factor of land in terms of water stress through variable rate irrigation. With the advent of modern developments in information technology, machine learning, Geographic Position System (GPS), Geographic Information System (GIS), drone-based monitoring, and automation, the IoT enabled precision irrigation system has become more strengthened now.

Drip irrigation in cabbage

Drip fertigation system

Automated irrigation system

Precision irrigation, data-driven decision-making, rainwater harvesting, conservation tillage, and drought-tolerant crops are just a few examples. Alongside technical measures, building community awareness, ensuring institutional support, and strengthening farmer training are also essential. Taken together, these strategies will help farming systems adapt to climate change, conserve resources, and maintain food security for future generations.

Water-smart irrigation

Water-smart irrigation refers to the use of modern tools and data-driven methods to supply crops with exactly the right quantity of water at the right time. By aligning irrigation schedules with crop needs and environmental conditions, this approach improves plant growth, reduces water waste, and makes farming more resilient to water scarcity. Its key objectives are:

- ***Conserving water:*** Compared to traditional irrigation, smart systems can cut water use by 20–50% through accurate delivery and reduced runoff.
- ***Enhancing crop performance:*** Supplying water in precise amounts supports healthier plants and higher yields.
- ***Protecting natural resources:*** Using less water also means lower energy demand for pumping, reduced groundwater depletion, less fertilizer leaching, and a smaller carbon footprint overall.

Smart irrigation technologies

- ***Drip irrigation:*** Drip (or trickle) irrigation supplies water slowly and directly to the root zone through a network of pipes and emitters. By reducing evaporation and runoff, it conserves water often cutting use by half or more compared with flood irrigation. Besides improving efficiency, drip system promotes uniform crop growth, healthier plants, and better yields. This also allows precise application of fertilizers (fertigation), reduce weed pressure, and can be automated to lower labour costs.
- ***Sprinkler irrigation:*** Sprinkler systems distribute water through nozzles that spray it over crops, creating an effect similar to natural rainfall. They provide even coverage, use less water than flood irrigation, and are suitable for uneven terrain. In addition, they help limit soil erosion, reduce nutrient losses, and save labour when automated.
- ***Soil moisture sensors:*** Soil moisture sensors measure the actual water content in the soil, giving farmers reliable data to guide irrigation. Common types include: Capacitance sensors detect moisture based on changes in the soil's dielectric constant; Time Domain Reflectometry (TDR), measures the speed of an electromagnetic pulse through the soil; and Tensiometers, record how much force plant roots must exert to extract water.
- ***IoT based automatic irrigation systems:*** Internet of Things (IoT) irrigation systems integrate real-time data from sensors, weather forecasts, and crop requirements. They use cloud platforms, smart valves, and mobile apps to automate water delivery, ensuring each crop gets just the right amount at the right time.

Automated surface irrigation system

The recent advances have facilitated the application of automation in both surface and groundwater irrigation which aid in achieving the target of maximum water use efficiency. Soil Moisture Sensor-Based Automatic Basin Irrigation System developed by Water Technology Centre, ICAR-IARI consists of three main units; a sensing unit, a communication unit, and a control unit. This system helps in water saving of 25% compared to the conventional manually controlled system in wheat.

- ***Remote sensing and drones:*** Remote sensing, especially with drones or satellites, helps monitor crop water status and detect stress early. Infrared imaging and indices like NDVI (Normalized Difference Vegetation Index) provide valuable insights into crop health. This information supports precise irrigation planning, reducing waste and improving yields.


Precision irrigation system in protected cultivation

Water-smart management practices

- ***Irrigation scheduling:*** Irrigation scheduling is the practice of deciding when and how much to irrigate so crops receive adequate water without waste. Decisions are based on crop type and stage of growth, weather conditions, and soil moisture.
- ***Crop needs:*** Different plants demand water at varying stages. For example, flowering and fruiting are critical periods. Pan evaporation measures evaporation from a standard pan to estimate crop water needs. Crop Water Stress Index (CWSI) compares canopy and air temperatures to detect plant stress.
- ***Weather:*** Temperature, humidity, and rainfall forecasts affect evaporation rates and must be factored in. Crop calendars gives long-term schedules suggesting irrigation timing, adjusted with real-time data.
- ***Soil moisture:*** Monitoring root-zone moisture ensures irrigation is applied only when necessary.
- ***Mulching:*** Mulching covers soil with organic or synthetic materials to conserve moisture, suppress weeds, and improve soil health. Plastic mulch retains moisture and warms soil but can pose disposal challenges. Organic mulch (straw, compost, leaves) decomposes, adding nutrients and improving soil structure. Biodegradable mulches (BDMs), made from starch or cellulose, provide similar benefits while naturally decomposing, though they can be more costly.
- ***Laser land leveling:*** This technology uses laser-guided equipment to smooth field surfaces, ensuring water spreads evenly. The practice improves crop germination, reduces erosion, enhances fertilizer use, and lowers fuel and labour requirements. By eliminating uneven patches, it also suppresses weeds and increases the cultivable area.
- ***Rainwater harvesting:*** Rainwater harvesting collects and stores runoff for future agricultural use. Methods include: Groundwater recharge through pits, trenches, or wells; direct irrigation from ponds or tanks, often linked to drip systems; livestock watering and aquaculture in farm ponds; and domestic use when properly filtered.
- ***Conservation agriculture:*** Conservation agriculture emphasizes minimum soil disturbance, permanent soil cover, and diverse crop rotations. Zero tillage allows crops to be sown without plowing, preserving soil structure and reducing evaporation and residue retention leaves plant material on the soil surface, protecting against erosion, conserving moisture, and enriching the soil over time.

Government initiatives for water-smart agriculture

To encourage efficient water use in farming, the Government of India and allied institutions have introduced several schemes and programmes. Two of the most significant are Pradhan Mantri Krishi Sinchayee Yojana (PMKSY-Per Drop More Crop) and initiatives supported by the National Bank for Agriculture and Rural Development (NABARD).

PMKSY (Per Drop More Crop): This flagship programme promotes micro-irrigation techniques such as drip and sprinkler systems, aiming to increase water-use efficiency and improve farm productivity. Its goals are to expand micro-irrigation coverage, reduce water consumption in water-intensive crops, and raise farmer incomes through precise irrigation. Through this yojana, farmers receive subsidies covering a major share of installation costs with higher assistance for small and marginal farmers. Funding is shared between the central and state governments, with special provisions for north eastern states, Himalayan regions, and Union Territories. Some states also provide extra subsidies to ease the farmer's share.

NABARD: NABARD contributes to water-smart agriculture by financing and supporting climate-resilient practices.

- **Micro Irrigation Fund (MIF):** Established with an initial ₹5000 crore to help states expand micro-irrigation.
- **Climate-smart projects:** Support for initiatives such as solar-powered pumps and efficient irrigation systems.
- **Capacity building:** Training and awareness programmes to familiarize farmers with modern irrigation and precision farming techniques.
- **Research and pilot projects:** Funding for innovations such as sensor-based irrigation systems to test and scale up new technologies.

SUMMARY

Water is the elixir of life and this precious natural resource needs to be preserved for ensuring safer environment. Owing to the climate change, the water resources are declining at significant rate which must be addressed urgently for ensuring sustainable development. In this context, we need to strengthen the sustainable water resource development and management through promotion and adoption of "water smart" agricultural practices. Integrated use of innovative techniques like drip irrigation, sprinkler systems, soil moisture sensors, automatic IoT-based irrigation systems, remote sensing and drones, optimized irrigation scheduling, mulching, laser land leveling, rainwater harvesting, and conservation agriculture will aid in paradigm shift towards efficient and sustainable water management in agriculture. Furthermore, it serves dual purpose of ensuring economic prosperity of Indian farmers and mitigating environmental degradation by conserving groundwater, reducing energy consumption for pumping, and minimizing the runoff of fertilizers and pesticides.

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Sub-surface drip fertigation for enhanced resource-use efficiency and profitability

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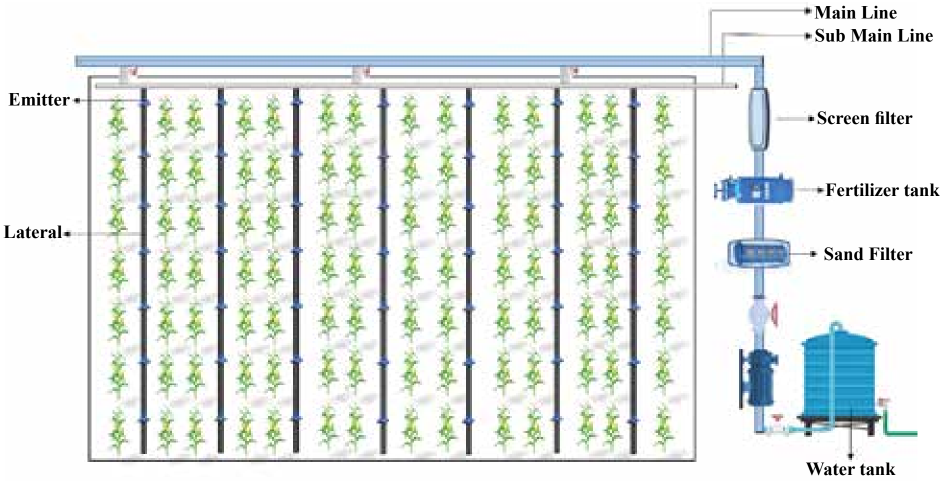
Unchecked population expansion and growing climate change-induced vulnerabilities in India and around the world are making the problem of water scarcity severer with each passing year. The nation's food bowl, the Indo-Gangetic plains region of India, has serious issues, such as groundwater depletion, low water productivity, inefficient water-use, nutrient deficiencies, and inefficient nutrient utilization. About 70% of the water used on Earth is used for agriculture, making it the biggest user of the freshwater supply, leaving little for other industrial uses. Conventional ways of applying irrigation water, such as flooding, result in poor water application; irrigation efficiency is about 35–40%, and water productivity is low, which affects long-term food security. In areas with limited water resources, sub-surface drip irrigation offers an alternative to precisely applying irrigation water. Because it makes it simple to apply water and nutrients to crops, increasing the efficiency of water and nutrient use, and thus, need to be popularized among the producers. Sub-surafce drip fertigation can boost nutrient and water-use efficiency (WUE) to 80% and 90%, respectively. In order to solve the problems of poor irrigation efficiency and water productivity and simultaneously increase the productivity of cereal-based cropping systems in a sustainable way, the most efficient water and nutrient management technique is discussed in the current article.

Keywords: Drip fertigation, Profitability, Water and nutrient-use efficiency

IN India's Indo-Gangetic Plains (IGP), water scarcity is a major issue because of erratic monsoons and rising needs for food production; therefore, effective irrigation techniques must be implemented immediately. The most used approach in India is surface flood irrigation, which results in a low water-use efficiency (WUE) and groundwater resource depletion. Therefore, enhancing crop productivity particularly in water-scarce areas will require conserving water resources and increasing WUE. Given the deteriorating groundwater supplies in northwest India, drip irrigation systems offer a viable way to alleviate the anticipated future water shortage. Although surface drip irrigation (SDI) is the most promising technique, it is labour-intensive to deploy and collect laterals throughout the year. Also, drip lines are exposed to sunlight, which makes them prone to deterioration and complicates cultural operations. Sub-surface drip irrigation (SSDI) systems could offer an alternate way to deal with these issues. SSDI systems increase the laterals' economic life by doing away with the requirement to anchor them during the crop-growing season. Additionally, the SSDI system lowers labour expenses, prevents weed growth, improves water and nutrient delivery to the active root zone, limits soil evaporation, and makes fertilizer application more effective. In addition, SSDI makes it simpler to carry out cultural operations than SDI. This system uses a technique called fertigation, which applies nutrients by sub-surface drip irrigation, to give nutrients straight to the root zone. Nutrient utilization efficiency is increased as a result of this focused administration of nutrients to the root zone, which also conserves the nutrients and lowers nutrient losses. The drip irrigation method was, first, mostly utilized for high-value crops like fruits and vegetables, but because of its dependability and durability, it is currently gaining popularity in agronomic crops. Depleted groundwater causes low water productivity and WUE in the Indo-Gangetic Plains of northwest India, especially in the area where rice-based agricultural systems predominate. As a result, it is crucial to accurately control irrigation water, safeguard groundwater supplies, and boost the water productivity of the cropping system based on cereals.



Design and installation of sub-surface drip irrigation

Installation and design

Main and sub-main pipes, laterals, emitters, flushing valves, pressure gauges, fertigation tanks, venturi, filters (especially sand and screen filters), are components of surface drip irrigation. Crop factor, soil texture, climate, and cultural customs all affect SSDI installation. For the installation of sub-surface drip laterals, the semi-mechanical and Quard-Raw machine methods are frequently employed. Depending on the soil's textural characteristics and crop rooting pattern, the laterals should be established 20–70 cm deep. There are two types of lateral pipes: Flexible, thin-walled laterals (0.15 mm to 0.30 mm) that are used for shallow installations, and thicker-walled laterals (0.38 mm to 0.50 mm) that are installed at deeper depths. Uneven water distribution in the root-zone caused by deeply positioned drip laterals may result in excessive water requirements and poor crop germination. Crop spacing affected the laterals' distance from one another, which typically spans from 0.25–5 m. In SSDI, the emitters are fixed inside the laterals (line source emitters); typically, one emitter has a discharge rate of two liters per hour. The SSDI has a discharge pressure of 135 kph (1.35 bar or 1.37 kg/cm^2). To add pesticides, fertilizers, or other additives to the irrigation water, SSDI systems frequently use venturi injectors (fertigation). The technique of applying nutrients and irrigation water directly to the crop root zone is known as fertilization. Although SSDI is more expensive to install initially, it saves money over time by conserving water and nutrients and increasing productivity and profitability.

Water-and nutrient-use efficiency

Sub-surface drip irrigation is an extremely accurate irrigation technique in terms of delivering nutrients and water to specific areas as well as determining when and how often to apply them for the best plant growth. SSDI reduces evaporation, seepage, deep percolation, and surface runoff, which is the primary way it saves water. The factors that contribute to increased crop growth and water productivity include regular water application at a reduced rate, surface retention of crop residue, the development of water-stable aggregates, and enhanced physical and chemical characteristics of the soil. Water consumption in the maize-wheat system was reduced by 54% as a result of SSDI in conservation agriculture, according to a study done at BISA-CIMMYT in Punjab. When compared to furrow irrigation, direct-seeded rice and wheat grown with residual mulch and SSDI yield considerably higher water productivity (0.75–0.84 kg/m^3 and 2.61–3.84 kg/m^3, respectively).

The term "nutrient-use efficiency" (NUE) refers to the efficiency with which a crop uses its nutrients to sustain growth and photosynthesis. Applying nutrients via SSDI helps minimize nutrient loss via surface runoff, volatilization, denitrification, and leaching. The crop's root zone receives applied nutrients directly, leading to a high nutrient utilization efficiency. Through sub-surface drip fertigation, 75% RDN + 4-split N treatment preserved 25–50% N fertilizer and enhanced the grain production in maize by 20–25.3%. In SSDI, 20% less

Maize and wheat crops under sub-surface drip fertigation (*Source*: Author's research field)

Table 1. Solubility of fertilizers recommended for fertigation in SSDI

Fertilizer	pH (1g/L at 200C)	Solubility (g/L)
Urea	5.8	1060
Ammonium Sulphate	5.5	750
Ammonium Nitrate	5.7	1950
Calcium Nitrate	5.8	1294
Diammonium Phosphate	7.8	692
Monoammonium Phosphate	4.7	374
Murate of potash	7.0	340
Sulphate of potash	3.7	110
Potassium nitrate	7.0	320

Source: International Potash Institute

nitrogen fertilizer is required for rice and wheat crops to get yields comparable to those of flood-irrigated crops. When fertilizing SSDI with five split applications, the mean nitrogen recovery efficiency is increased by 16.5% and 29%, respectively, in comparison to furrow irrigation in maize and wheat.

Fertigation

Water-soluble fertilizers can be efficiently applied at the right location with drip fertigation systems. The fertilizer material's solubility determines how fertilizer is applied via drip irrigation. Although nitrogen is the ingredient most frequently used, vegetables and other food crops also frequently need potassium and phosphorus. While nitrogen fertilizers are readily soluble in water and can be delivered via SSDI, phosphorous fertilizers have the potential to precipitate in drip laterals, which can cause blockage. According to the kind of fertilizer, the degree of solubility varies. For example, potassium nitrate (13-0-46) has a low solubility of about 1:8, meaning that 1 kg of dry fertilizer dissolves in 8 liters of water. Ammonium nitrate (34-0-0) and calcium nitrate (15.5-0-0) have a high solubility of roughly 1:1, whereas potassium chloride (0-0-62) has a solubility of 1:3. The solubility of dry phosphorous

Table 2. SSDI performance in India's main cropping systems

Crop/cropping system	% increase in yield	Water saving
Rice-wheat	2.5% in rice 25% in wheat	75% in rice 45% in wheat
Wheat-mungbean-maize	28–58% in wheat 15–24% in mungbean 28-61 % in maize	40 % in wheat 22 % in mungbean and 23 % in maize
Maize-wheat	30% in CA with SSD over conventional tillage with flooding	54.15%
Rice	10–15% decrease in yield over flooding	40–45 %
Rice-wheat	19% in rice 14.75% in wheat	48–53% in rice and 42–53% in wheat
Maize	20–25.3% higher yield than conventional irrigation	-
Maize	25–50% N save	-

Table 3. Economics of SSDI in rice-wheat cropping system

Particular	Cost
33.75 cm spacing drip cost (with 80% subsidy and a 15-year lifespan)	₹ 2769/ha
67.5 cm spacing drip cost (with 80% subsidy and 15-year life)	₹ 1530/ha
Surface drip cost (with an 8-year lifespan and an 80% subsidy)	₹ 5108/ha
33.75 cm spacing drip cost (without subsidy and 15-year life)	₹ 13,847/ha
67.5 cm spacing drip cost (without subsidy and 15-year life)	₹ 7650/ha
Surface drip cost (without subsidy and 8-year life)	₹ 25,540/ha

Source: Sidhu *et al.* 2019

fertilizers is approximately 1:2.5 that of nitrates. The main benefits of fertigation over the traditional way of application are lower labour, fertilizer, energy, and fertilizer use efficiency.

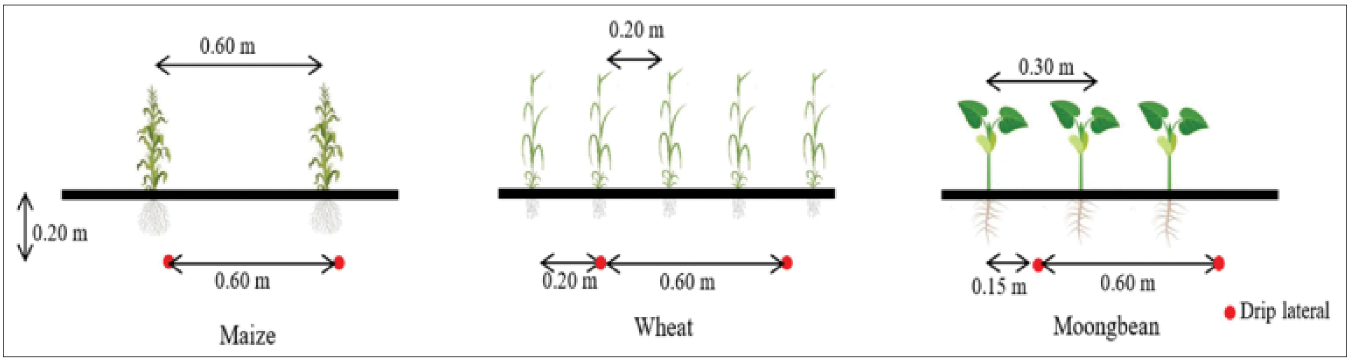
Productivity

In SSDI, water is sprayed straight onto the root zone, meeting agricultural water needs and preventing moisture stress. The root zone can also receive nutrient applications in accordance with crop needs. Water and nutrients work together in the root zone to increase crop yields and boost the efficiency of water and nutrient utilization. In addition, there is a noticeable decrease in the prevalence of diseases, weeds, and insect pests, which eventually improves crop quality and output.

Economics

The annual cost of the SSDI system is usually lower than SDI due to the initial installation cost and longer life span. The tractor-operated machine used to install SSDI reduces cost. The lifespan of an SSDI system is 10–15 years, but that of an SDI system is 6–8 years. With the SSDI system, laterals and inlines are protected from sunshine and rodents and do not need to be removed during crop sowing or harvesting. The government of

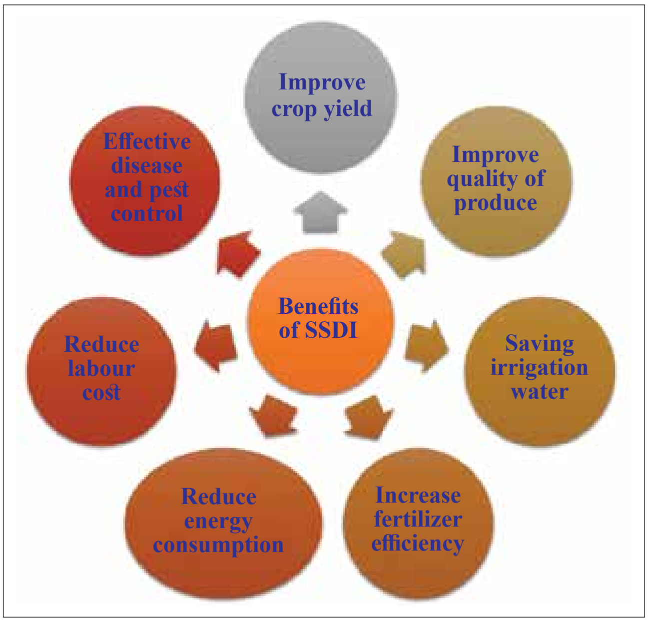
Fertigation through sub-surface drip system
(*Source*: Author's research field)



Cross-sectional view of experimental setting depicting crop rows and relative position of sub-surface drip laterals (*Source:* Daina *et al.* 2023)

Table 4. Challenges and solutions of SSDI

Challenges	Solutions
Emitter clogging	Frequent cleaning of the sand and screen filters Flushing of drip laterals at the end of every crop season Acid treatment: HNO_3, H_3PO_4 and HCL
Damage from rodents and other animals	Phorate 10G application
High cost of drip	Initially, it has a high drip cost, but over the long term, it is cost-effective for farmers (life duration of 15 years). The payback period is only 7 years and the remaining years economical The benefit-cost ratio is raised by choosing high-value market crops.
Restricted root development of crops	Numerous factors influence root growth, including soil and plant properties, irrigation system design (number of emitters per plant, location, and emitter discharge rate), and management factors (amount and frequency of water application).



Advantages of SSDI system in crops/cropping system

India is subsidizing 80% of the real cost of drip irrigation, which makes it more cost-effective for farmers.

Case study

The Indian Agricultural Research Institute in New Delhi conducted a study on the effects of surface drip irrigation (SDI) and SSDI systems on water and crop productivity of wheat-mungbean-maize cropping systems. In contrast to surface flood irrigation and fertilizer application, the results demonstrated that SSDI at 0.8 ETc with 100% fertigation of appropriate doses of NPK fertilizers boosted irrigation water productivity by 118%, total water productivity by 45% and system productivity by 5.4%. Additionally, fertigation with SSDI or SDI lowered the amount of fertilizer needed for this cropping system by 20% while still producing a yield comparable to that of the conventional system. In maize, moongbean, and wheat, fertilization with 60, 80, and 100% of the prescribed NPK levels produced notable yield increases. Additionally, grain yields generated with irrigation scheduling at 0.8 ETc were almost 10% higher than those produced at 0.6 ETc.

SUMMARY

In India's Indo-Gangetic Plains, sub-surface drip irrigation may provide a solution to the water shortage. Reduced evaporation, improved nutrient absorption, and less water wastage are a few among many advantages of SSDI. By supplying nutrients and water directly to the root zone, this technique improves water and nutrient conservation and increases its effectiveness. SSDI turns out to be more profitable over time, even with higher initial expenses on installation. When comparing SSDI to traditional methods, studies show notable yields and significant reductions of water and fertilizer consumption. Together, the Indian and state governments are providing significant subsidies, maximum between 70% and 90% depending upon kind of farmer and size of landholding, to encourage the broad use of microirrigation systems. Although there are drawbacks, such as emitter blockage and rodent damage, they are outweighed by the bigger advantages. All these aspects considered together, SSDI offers an accurate and effective irrigation technique that is essential for sustainable farming and resolving water scarcity and also the nutrient deficits (when nutrients are applied through drip fertigation) in areas, like the Indo-Gangetic Plains.

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Carbon farming:

Practices and challenges

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Agriculture and climate change are interconnected, each profoundly influencing the other as agriculture is both a contributor and victim of climate change. To attain carbon neutrality, we have to shift our focus from carbon dioxide emissions towards carbon dioxide removal (CDR) from the atmosphere. Even CDR is an integral part of IPCC scenarios that aim to limit global warming to 1.5°C relative to pre-industrial levels. Compared to natural forests, carbon is lost much more from our cultivated lands because crops are harvested every year, soil is tilled annually, and faulty agricultural practices are employed. Hence, to attain carbon neutrality, we should adopt a novel approach known as carbon farming.

Keywords: Carbon neutrality, Climate change, Novel approach

ENHANCING soil organic carbon is a pre-requisite to carbon farming, as it is the major pool for soil organic carbon sequestration, accounting for nearly three times as much carbon as aboveground biomass and twice the amount of carbon present in the atmosphere. Carbon farming is a component of climate-smart agriculture in which carbon is removed from the atmosphere, i.e. sequestration of carbon, and that sequestered carbon is conserved and locked in soil.

Geological sequestration

It involves storing anthropogenic carbon dioxide (CO_2) deep underground in geological formations to prevent it from entering the atmosphere. It is generally injected deep underground (generally more than 800 m) in minute pores and spaces in rock structures and the impermeable cap rocks act as a seal to ensure safe storage of CO_2.

Oceanic sequestration

Oceanic sequestration involves storing carbon in the oceans, either by enhancing natural processes or direct injection. The sequestration of carbon in the ocean involves the following processes.

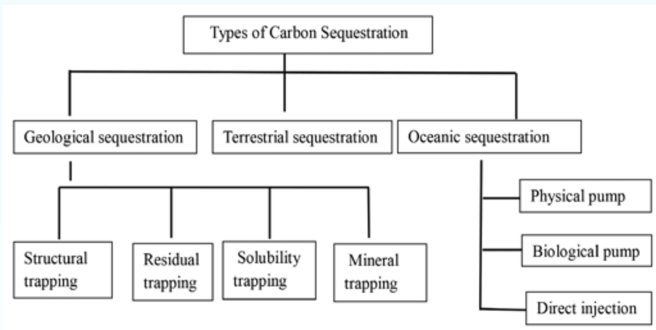
Biological pump: The marine organisms' phytoplankton absorb CO_2 during photosynthesis, and after their death, they sink, taking carbon to deeper ocean layers.

Physical pump: CO_2 dissolves in cold deeper ocean water and is transported by ocean currents.

Direct injection: CO_2 is injected into deep ocean layers, where high pressure and low temperature keep it dissolved.

Terrestrial sequestration

It involves storing carbon in forests, soils, and vegetation. Terrestrial sequestration mainly occurs through the process of photosynthesis, whereby plants absorb CO_2 and convert it into organic carbon compounds. These compounds are stored in the biomass of plants, including leaves, stems, branches, and roots, as well as in the soil, where carbon is incorporated into organic matter through litterfall, root exudates, and microbial activity.



Mass balance for carbon

The mass balance for carbon in the ecosystem can be expressed by the following equation:

Input – Output = Storage

Inputs, Photosynthesis and soil amendments; Outputs, Plant and microbial respiration, and Emissions of volatile organic compounds (VOCs); Storage, Plant and microbial biomass, and soil carbon as SOC and SIC pools.

Strategies for promoting carbon farming through climate action plans

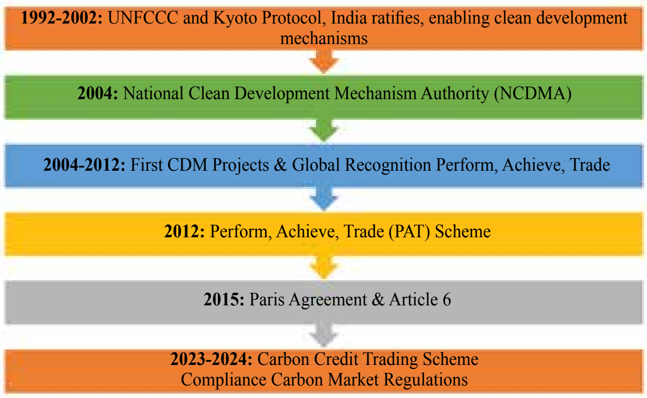
National action plan on climate change: The National Action Plan on Climate Change (NAPCC) was released by the Prime Minister on June 30, 2008, and outlines a national strategy that aims to enable the country to adapt to climate change and enhance ecological sustainability. This comprehensive framework encompasses the National Mission for a Green India and the National Mission on Sustainable Agriculture, which emphasizes climate-resilient practices and resource conservation.

National mission on sustainable agriculture: The National Mission for Sustainable Agriculture (2014-15) is a key component of the National Action Plan on Climate Change (NAPCC), which emphasizes sustainable farming by enhancing soil health, promoting efficient water use, and encouraging the adoption of organic agriculture. It provides subsidies and financial aid to encourage the adoption of climate-resilient technologies, improved soil management, and water conservation practices, all of which contribute towards carbon farming.

Carbon capture utilization and storage technology (CCUS): According to the IPCC, CCUS involves capturing a concentrated stream of CO_2 from industrial or energy-related sources, conditioning and compressing it, and transporting it to secure sites for long-term storage, thereby preventing release into the atmosphere. Formerly termed Carbon Capture and Storage (CCS), the concept now includes utilization pathways, where captured CO_2 is repurposed. A major application is enhanced oil recovery (EOR), in which CO_2 is injected into depleted reservoirs to increase crude oil extraction while sequestering the gas underground. CCUS is thus a dual-purpose technology mitigating emissions while supporting industrial productivity.

Carbon credit trading scheme: Launched by the Ministry of Agriculture and Farmers Welfare, this scheme enables farmers and organizations to register GHG mitigation projects and earn tradable carbon credit certificates through the voluntary carbon market (VCM). One carbon credit equals one metric tonne of CO_2 equivalent reduced, avoided, or removed. Verified standards like the VCS and Gold Standard provide protocols for measuring and validating reductions in agriculture. By adopting eco-friendly practices and securing verification, farmers can generate credits to sell to companies seeking emission offsets. This not only supports climate change mitigation but also provides farmers with additional income.

National agroforestry policy and sub-mission on agroforestry (SMAF): India was the first country



Historical foundation behind carbon credits

in the world to adopt a dedicated agroforestry policy in 2014. Its main objective was to integrate trees with crops and livestock systems, increasing productivity, income, and environmental benefits. It serves as an important component of carbon farming as agroforestry enhances carbon sequestration, improves soil health, and diversifies farmer income.

Sub-mission on agroforestry (SMAF): This was launched in 2016 onwards under the National Mission for Sustainable Agriculture (NMSA). Its main objective is to incentivize farmers for adopting agroforestry practices by providing financial assistance for nursery development, sapling distribution, and plantation.

Green credit programme (GCP): The Green Credit Initiative was launched by the Honorable Prime Minister during 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 28) as part of the government's Lifestyle for Environment (LiFE) movement. To support this, the Green Credit Rules, 2023 were notified on 12th October 2023 under the Environment Protection Act, 1986. Under this programme Green Credits (GCs) are awarded to individuals or organizations undertaking activities like tree plantation and other eco-friendly practices. The initiative encourages voluntary positive environmental actions, with the initial phase focusing on plantations on degraded lands, wastelands, and watershed areas managed by Forest Departments. The Green Credit Rules, 2023, operate separately from the Carbon Credit Trading Scheme, 2023, meaning GC generation is independent of carbon credits. The GCP covers a wide range of activities, including, tree plantation, water management, sustainable agriculture, waste management, air pollution reduction, mangrove conservation and restoration, eco mark label development, and sustainable buildings and infrastructure.

Agro-techniques for carbon farming

Crop management:

- **Cover crops:** Cover crops play a vital role in carbon farming by acting as a link between atmospheric carbon dioxide and long-term soil carbon storage. When these crops are grown between main crop cycles, they capture carbon dioxide through

Wheat + lentil

Direct seeded rice sown by happy seader under zero tillage

photosynthesis and channel it into their roots, stems, and leaves. When incorporated into soil, cover crop biomass enriches organic matter, enhances fertility, and increases soil carbon. Their roots release organic compounds through rhizodeposition, stimulating microbial activity and promoting humus formation. Deep-rooted species are particularly effective as they deposit carbon in deeper soil layers, making it less vulnerable to decomposition. Additionally, cover crops protect existing soil carbon by forming a surface cover that reduces erosion and preserves carbon-rich topsoil. Thus, cover crops play a dual role-capturing new carbon while safeguarding stored carbon-contributing significantly to soil health and long-term carbon sequestration.

- **Biochar application:** Biochar is produced through pyrolysis. During this process, a large portion of the carbon in biomass is converted into stable aromatic carbon rings. Unlike the crop residues or manure that decompose quickly and release CO_2, biochar is highly resistant to microbial breakdown. It can remain in soils for hundreds to thousands of years, effectively locking carbon in soil.
- **Terra-Preta:** *Terra Preta* (meaning "black earth" in Portuguese) is an ancient biochar-based soil management technique that has a direct link to carbon farming. It is created by indigenous communities found in the Amazon Basin and made by adding charcoal (biochar), food waste, manure, bones, and organic residues into nutrient-poor tropical soils. The charcoal (biochar) in *Terra Preta* is highly stable. It resists decomposition as it locks carbon in the soil for centuries, making it one of the ancient models of permanent carbon sequestration.
- **Zero-Tillage:** ZT eliminates repeated ploughing operations, lowering diesel consumption and reducing CO_2 emissions from machinery. Without ploughing, soil aggregates remain stable and trap organic carbon within, physically protecting the carbon from microbial attack.
- **Organic mulch:** Organic mulching plays an important role in carbon farming because it directly adds organic matter to the soil while simultaneously protecting existing soil carbon. When crop residues, straw, leaves, or compost are applied to the soil surface, they slowly decompose and enrich the soil with carbon-rich organic matter, thereby increasing soil organic carbon stocks. At the same time, the mulch layer shields the soil from direct sunlight, wind, and erosion, reducing the chances of carbon loss through oxidation and surface runoff.

Livestock management :

- **Rotational grazing:** Well-managed rotational or adaptive multi-paddock grazing allows pastures to recover, increasing root biomass and soil organic carbon. This practice also prevents overgrazing, which can degrade soil and reduce carbon storage

Biochar application

Pigeon pea residue in ZTW

potential. When pastures are allowed to rest, plants recover and grow deeper root systems. These roots deposit organic matter into the soil, which increases soil organic carbon over time, and this root system also improves soil structure and water retention, subsequently promoting carbon storage.

- **Manure management:** Composting livestock manure before application to fields can stabilize carbon and reduce methane and nitrous oxide emissions. Direct application of manure to croplands, especially in combination with cover crops, contributes to soil organic matter, improving soil health and carbon storage. When manure is applied to fields, it adds organic matter to the soil. This organic matter, when incorporated into soil aggregates, stores soil organic carbon for longer periods.
- **Integrating silvo-pastoral systems:** Trees along with livestock grazing could provide additional carbon sequestration through woody biomass, while also offering shade and fodder for animals. Agroforestry with livestock can significantly increase carbon stocks both above and below ground.

Forestry management :

- **Reforestation:** It is one of the most effective strategies in carbon farming because it directly removes CO_2 from the atmosphere and stores it in biomass and soils. When trees are planted on previously deforested or degraded land, they act as carbon sinks, absorbing CO_2 through photosynthesis and converting it into biomass. Over time, this biomass stores large amounts of carbon that would otherwise contribute to climate change. Reforestation also improves soil carbon sequestration. As the trees grow, they drop leaf litter and organic residues that decompose, increasing the soil organic carbon content.
- **Bamboo farming:** It could serve as a powerful tool for carbon farming because bamboo is a fast-growing, perennial plant with a high capacity for carbon sequestration. Unlike many trees, bamboo can grow very quickly, allowing it to capture CO_2 from the atmosphere at a much faster rate than conventional forests. Also, its extensive root system contributes to long-term carbon storage in the soil by adding organic matter and improving soil structure. This soil carbon can remain stable for decades, enhancing overall soil fertility and resilience.
- **Alley cropping:** Also known as hedgerow intercropping, it is the integration of trees or shrubs with annual crops in the same field, creating a system that captures and stores carbon both above and below ground. In this practice, rows of trees or shrubs are planted at regular intervals, and crops grow in the "alleys" between them. The trees and shrubs in alley cropping act as carbon sinks, absorbing atmospheric CO_2 through photosynthesis and storing it as above-ground biomass in trunks, branches, and leaves.
- **Mangrove restoration:** Mangroves are a part of "blue carbon" ecosystems as they sequester carbon in both plants and sediments more effectively than most terrestrial ecosystems. Mangroves store a large amount of carbon below ground in waterlogged soils. Their dense root systems trap sediments and organic matter, which decomposes very slowly due to anaerobic conditions, allowing carbon to remain stored for centuries.

Large cardamom with Ficus tree

Challenges in carbon farming

- Accurate quantification of how much carbon dioxide is emitted and converting it to carbon credits is a difficult task.
- Carbon sequestration is not permanent, since stored carbon in the soil can still be lost unless further protected.
- Farmers may be hesitant to adopt carbon farming practices due to uncertainty about financial returns, lack of awareness, or the need for upfront investment.
- Carbon credit markets are still fragmented, lack transparency, and the prices of carbon credits are volatile.
- Changes in rainfall, rising temperatures, and extreme weather events may compromise the reliability of carbon sequestration efforts.

SUMMARY

India is in the preliminary stage of carbon farming, and for strengthening it, a powerful framework is needed that can connect farmers, industries, and the government together to build a robust carbon credit system, enabling this carbon farming to contribute to India's GDP. Governments must create stable, long-term policies that support carbon farming within broader climate action strategies and provide low-interest credit grants for farmers transitioning to carbon-friendly practices. The Indian government should establish strong ties with the developed countries so that it can earn by selling carbon credits to them for reducing their emissions. Hence, there is ample scope in carbon farming, and to save the planet, it is necessary to shift from soil-depleting farming to carbon-enriching farming.

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Integrated crop management technology

for resilient agri-food systems and environmental stewardship

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Agriculture contributes ~16% to India's GDP and sustains nearly half of its population, making it central to food security and rural livelihoods. The Green Revolution enhanced self-reliance in foodgrains production and drove growth through scientific and policy interventions. However, conventional practices have degraded soil health, water resources, and biodiversity while reducing factor productivity and resource use efficiency. Challenges include groundwater decline, soil organic matter loss, pest and disease resurgence, pesticide residues, and herbicide resistance. Coupled with socio-economic shifts such as urbanization, labour migration, and changing diets, these issues necessitate climate-resilient, resource-efficient, and sustainable agricultural approaches.

Keywords: Environmental security, Food safety and quality, Integrated crop management, Resilient agri-food systems, Sustainable agriculture

ACCORDING to the FAO, Integrated Crop Management (ICM) has recently emerged as a comprehensive and more impactful strategy compared to managing soil, water, nutrients, crops, pests, diseases, and energy in isolation. ICM brings together the most appropriate agronomic practices needed to achieve higher productivity. These include methods of tillage and crop establishment, Integrated Nutrient Management (INM), Integrated Weed Management (IWM), Integrated Water Management (IWrM), Integrated Disease Management (IDM), and Integrated Pest Management (IPM), among others. It also emphasizes the combined management of tillage and water resources in a coordinated manner. This approach is especially valuable for small and marginal farmers since it reduces reliance on costly external inputs and promotes better use of on-farm resources. By addressing not only the production aspects but also socio-economic and environmental dimensions, ICM provides a holistic pathway to sustainable agriculture. Its goal is to identify practices that are safe, efficient, and adaptable, ensuring both immediate productivity and long-term ecological and economic benefits. In above context, there is urgent need to have appropriate resource-management strategies in crop production. ICM is a pragmatic approach which includes IPM, soil, social and environmental management. Literary, ICM is composed of 3 words, namely integrated, crop and management:

- Integrated refers to a holistic, site-specific approach that considers the entire production system as one unit.
- Crop signifies the inclusion of every component of crop husbandry and cultivation practices.
- Management encompasses the processes of planning, goal-setting, implementation, supervision, evaluation, and attaining the desired outcomes.

ICM brings together a range of farming practices such as crop rotation, tillage methods, selection of suitable varieties, and the careful use of fertilizers and pesticides in an environment-friendly way. More importantly, ICM represents a structured system of farming that requires careful planning, implementation, target setting, and regular monitoring. This approach merges advanced crop production technologies with fundamental principles of good agricultural practice, aiming to reduce wastage, improve energy efficiency, and lower pollution levels. It is not only a whole-farm approach but also a long-term strategy. ICM ensures that farm enterprises remain profitable while being environmentally responsible and resource-sensitive. The system focuses on sustainable crop production by protecting and enriching natural resources, while ensuring the supply of safe and quality food in an economically feasible way. Its foundation lies in understanding the interactions between biological processes, ecological systems, and land management practices. In essence, ICM emphasizes efficient food and

Major components of integrated crop management (ICM)(*Source*: Choudhary *et al.* 2020)

product supply, reduced dependence on non-renewable inputs, conservation of soil, water, and air quality, and the protection of biodiversity within agricultural landscapes. The approach is guided by five key principles, viz. Food security, Environmental security, Economic viability, Social acceptability, and Food safety and quality.

Therefore, ICM practices hold considerable potential for enhancing yield, improving productivity, and raising profitability, particularly for smallholder farmers. These practices are designed and fine-tuned in partnership with farmers so that they address local requirements and constraints effectively. As new research insights and technologies emerge, ICM options must also be revised and refined to remain relevant. When such technologies are developed through active participation of farmers, the chances of their acceptance and long-term adoption increase substantially.

ICM: An innovative approach for resilient agri-food systems

ICM offers an alternative framework for crop production that emphasizes the conservation and enhancement of natural resources while ensuring the supply of high-quality food in a cost-effective and sustainable manner. It takes into account integrated tillage and water management strategies in a holistic way. ICM merges time-tested traditional practices with relevant modern technologies to strike a balance between profitable crop production and environmentally sound farming. As a whole-farm strategy, ICM provides the foundation for efficient, productive, and profitable agriculture that is both economically feasible and ecologically responsible. In practice, ICM reflects the principles of sound agronomy and effective crop husbandry. It can be described as the combined application of compatible technologies that are tailored to farmers' needs, thereby improving crop productivity in an environmentally sustainable way. It is called by different names in different countries: Integrated crop and resource management in Indonesia and ICM in the Philippines. It combines the best of modern technology with some basic principles of good farming practice. ICM is a whole farm long term strategy and thus it cannot be applied to one crop or one field or one season. ICM involves multidisciplinary research and the basic components are soil management, crop rotation, crop protection, crop nutrition, wild life, landscape, energy, waste and pollution as well as organizational management. ICM offers particular advantages to small and marginal farmers as it reduces reliance on costly external inputs and encourages greater use of locally available farm resources. It follows a whole-farm, site-specific strategy that typically includes:

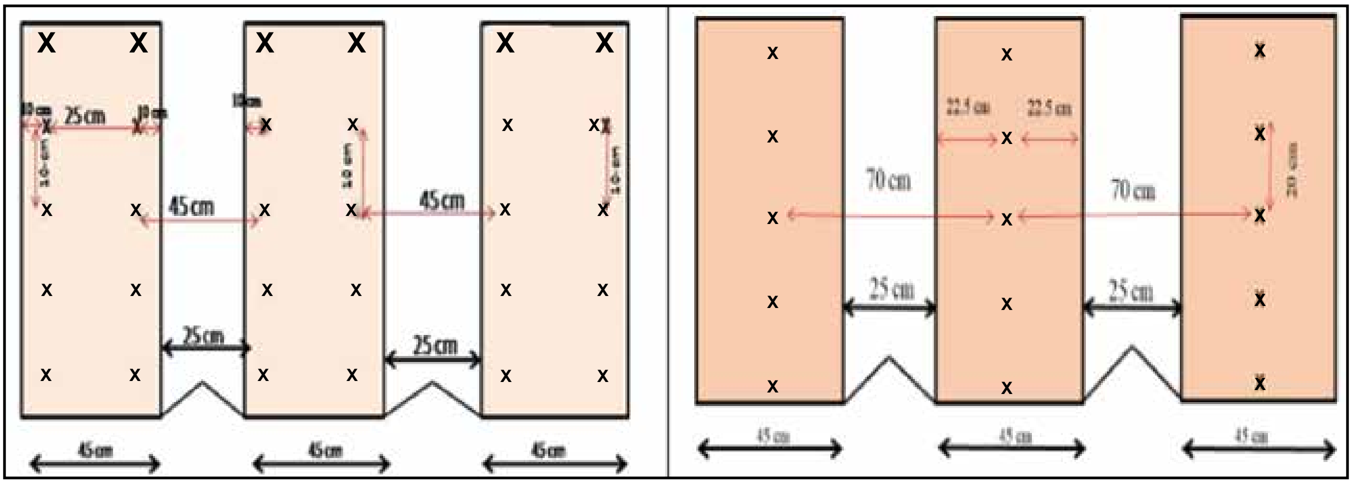
- Adoption of crop rotations to maintain soil fertility and break pest cycles
- Application of suitable tillage and cultivation methods
- Careful selection of crop varieties adapted to local conditions
- Reduced dependence on synthetic inputs such as chemical fertilizers, pesticides, and fossil fuels
- Protection and improvement of the farm landscape
- Promotion of wildlife-friendly habitats within the production system

Table 1. Key elements of integrated crop management

Component	Objective
Reduced tillage and soil conservation practices	Economical preservation of soil structure and long-term fertility
Application of biofertilizers, legumes, green manures, and agroforestry methods	Enrichment of soil fertility and enhancement of microbial activity and diversity
Integrated pest and disease management	Cost-effective and eco-friendly crop protection with minimal chemical residues
Crop diversification and rotational farming	Disruption of pest, disease, and weed cycles
Efficient utilization and safe disposal of crop and livestock residues	Recycling of resources to improve soil quality, plant health, and human well-being
Conservation and promotion of ecological diversity	Protection of soil health and preservation of biodiversity
Reduced dependence on external inputs and fossil fuels	Lower production expenses and minimization of environmental harm

Components of ICM

Basic components of ICM are tillage and crop establishment methods, INM, IWM, IWrM, IDM and IPM, efficient farm machinery management, energy management and even financial management.



Raised-bed land configuration and planting geometry for (a) Soybean and (b) Pigeonpea

Integrated crop management includes virtually everything that happens on the holding, including livestock management, where relevant.

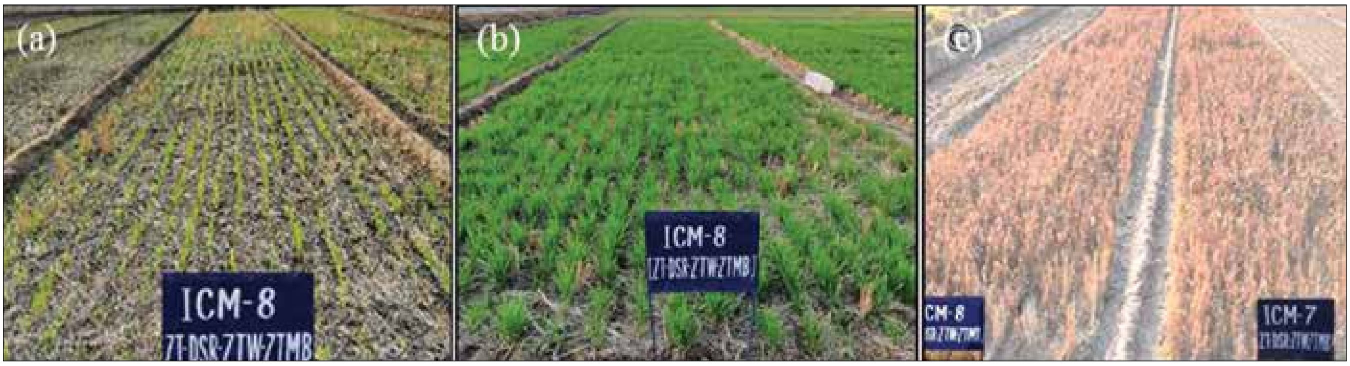
Tillage management: Tillage and residue management play a vital role in crop growth, soil health, and sustainability. Tillage improves seedbed preparation, root development, and weed control, while long-term effects include maintaining soil productivity and conserving resources. India generates ~650 million tonnes of crop residues annually, with ~92 million tonnes burnt, causing pollution, nutrient loss, and health hazards. Continuous tillage degrades soil properties, whereas conservation tillage (reduced/no-till) improves soil structure, water conservation, SOC sequestration, and cropping intensity, while reducing GHG emissions. Thus, adopting suitable tillage and residue management practices is essential for sustainable crop production and environmental health.

Land configuration and crop establishment methods: Land configuration and crop establishment methods are crucial for soil productivity, water and nutrient use efficiency, and soil quality. Proper configurations improve soil biological activity, organic matter, and moisture while reducing erosion, runoff, and nutrient losses. Ridges warm and dry faster than flat-beds, influencing soil temperature and water dynamics. Suitable land configurations enhance crop growth and resource-use efficiency; for instance, soybean performs well on raised beds (70 cm wide) with two rows sown 25 cm apart on the platform and 10 cm spacing at edges and between plants. Such methods optimize productivity, soil health, and sustainability in cropping systems.

Integrated nutrient management (INM): Declining soil fertility and mismanagement of plant nutrients have made world's increasing demand for food a more difficult task. Adequate plant nutrient supply holds the key to better foodgrain production for sustaining livelihoods. Although a wide range of nutrient management strategies exist for different crops across the globe, many farmers fail to apply fertilizers at the recommended levels due to high costs and limited affordability. In this context, INM becomes vital emphasizing the combined use of organic manures, crop residues, green manures, biofertilizers, and legumes along with inorganic fertilizers to supply the nutrient requirements of various crops and cropping systems. Excessive reliance on chemical fertilizers alone has already resulted in environmental concerns such as soil degradation and contamination of water bodies. Hence, for achieving and maintaining higher crop productivity, the ICM approach must integrate INM with other complementary practices to ensure balanced and sustainable nutrient supply.

Integrated weed management (IWM): IWM refers to keeping weed populations at levels low enough to avoid significant economic loss in crops. It is a strategy that combines all feasible, safe, and cost-effective measures whether ecological, economic, or toxicological to ensure weeds remain below the Economic Threshold Level

Integrated crop management trials under a fixed maize-wheat rotation included: (a) Conventionally tilled plots following wheat harvest, (b) Plots with wheat residues retained, (c) Incorporation of mungbean as an additional crop, and (d) Incorporation of sesbania green manure within wheat residue-retained plots.



Integrated crop management rice-wheat rotation's experiment - (a) ZT direct seeded rice, (b) ZT wheat, and (c) knocked down mungbean

(ETL). The principle behind IWM is to apply multiple techniques in a coordinated manner so that crop yields are maximized at the lowest possible cost, while also considering environmental and socio-economic conditions of the production system. In practice, IWM adopts a long-term management perspective, drawing on diverse methods such as mechanical and manual removal, cultural and ecological practices, biological control agents, and judicious use of herbicides.

Integrated water management (IWrM): IWrM plays a key role in achieving sustainable agriculture. Although irrigated land accounts for only about 18% of the world's cropland, it contributes nearly 40% of total food production. However, irrigation efficiency remains poor, as just around 55% of the water applied is effectively used by crops, while competition for water continues to increase from domestic and industrial sectors. Improving water use efficiency (WUE) through practices such as conservation tillage, reduced tillage, and no-till farming helps conserve soil moisture, limit erosion, and support more intensive cropping, particularly in semi-arid zones. Moreover, making use of marginal water resources including saline, reclaimed, and drainage water alongside the adoption of advanced irrigation methods offers practical solutions to water scarcity and underpins sustainable crop production.

Integrated disease management (IDM): IDM is a holistic approach to reduce crop losses from pathogens (fungi, bacteria, viruses, nematodes, phytoplasmas) by combining cultural, biological, mechanical, and chemical methods. Unlike reliance on a single strategy, IDM emphasizes minimal pesticide use, prioritizing host-plant resistance, clean planting material, seed treatment, biological control, and good cultural practices. Modern crop protection products are increasingly target-specific and eco-friendly, reducing harm to beneficial organisms. Effective IDM requires crop rotation, farm hygiene, resistant varieties, natural predators, and precise chemical use. Wider adoption of IDM is essential to minimize 10–15% yield losses, enhance sustainability, and safeguard food security.

Integrated pest management (IPM): IPM is a sustainable strategy that combines cultural, biological, and chemical methods to manage pests while minimizing ecological disruption. Overreliance on pesticides has caused resistance, pest resurgence, and residue problems, making IPM essential for food security. Traditionally, Indian farmers relied on cultural and mechanical practices before synthetic pesticides. IPM emphasizes predicting pest incidence, proper identification, and selecting effective, safe, and economical control measures. When chemicals are necessary, they must be used judiciously—choosing the right product, dose, timing, and application method. Training operators and integrating eco-friendly approaches ensures sustainable crop protection and reduced environmental impact.

Integrated energy management (IEM): IEM focuses on optimizing farm energy use for sustainability and profitability. Agriculture relies heavily on energy for tillage, irrigation, machinery, and inputs, yet efficiency often remains overlooked. Preparing crop-wise energy budgets and adopting renewable sources can enhance efficiency. Optimal energy input can raise yields by up to 30%, while conservation agriculture significantly reduces costs, as 25–30% of energy is spent on field preparation. Zero tillage with crop residue retention improves energy efficiency, soil health, and ecosystem services. Use of energy-efficient tools like seed-cum-fertilizer drills further lowers costs, boosts yields, and supports sustainable crop production.

SUMMARY

Integrated Crop Management (ICM) is a holistic approach that balances food production with environmental care, farmer welfare, and resource sustainability. Conventional farming practices have led to groundwater depletion, declining soil fertility, low resource-use efficiency, pest and disease resurgence, herbicide resistance, and environmental degradation. ICM integrates tillage, nutrient, water, weed, pest, and energy management to enhance productivity, profitability, and input-use efficiency while conserving soil, water, and energy. Despite its potential, systematic evaluation of ICM modules across crops and agro-ecologies remains limited. Developing region-specific ICM strategies is important to address resource vulnerabilities and climate change threats for sustainable agriculture.

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Herbicide tolerant crops

for weed management

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Weeds are a major constraint in Indian farming, often causing greater yield losses than insects or diseases. Manual weeding is becoming less viable due to labour shortages and rising costs. Herbicide-tolerant (HT) crops provide effective, broad-spectrum weed control, reduce labour, and support resource-conserving practices like direct-seeded rice and zero-tillage. Globally, HT crop varieties in soybean, maize, cotton, and canola have delivered productivity gains but raised concerns about herbicide resistance and environmental impact. In India, non-GM imidazolinone-tolerant rice varieties (Pusa Basmati 1979, Pusa Basmati 1985, CR Dhan 807) and hybrids (SAVA 127, SAVA 134 Fullpage) are released, while HT mustard and others are under development. HT crops can cut weeding costs, boost yields, and reduce drudgery especially for women but sustainability depends on careful management. Over-reliance on one herbicide may accelerate resistance. Integrating HT crops within an integrated weed management framework and strengthening policies and extension can enhance food security and profitability.

Keywords: Challenges, Herbicide-tolerant crops, Innovation, Integrated weed management

WEEDS are among the most destructive yet underestimated threats in Indian agriculture. Unlike insects or diseases, they grow unnoticed alongside crops, competing for water, nutrients, sunlight, and space, while harbouring pests, clogging irrigation systems, and contaminating harvests with seeds. If not managed early (within the first 30–40 days after sowing) weed damage can cause permanent yield losses of 20–40% in crops like rice, wheat, maize, soybean, and cotton, and may even result in total crop failure. Traditionally, farmers relied on manual weeding, spending long hours hand-pulling weeds or using hoes and animal-drawn weeders. Selective herbicide use became common only in the late twentieth century. Today, labour shortages, rising wages, fragmented landholdings, and shifting weed populations make older methods less practical. Herbicide-tolerant (HT) crops provide a modern solution, enabling farmers to apply broad-spectrum herbicides safely to control diverse weeds efficiently, protect yields, and secure livelihoods.

Weed problems in major crops

Rice: The gradual shift towards Direct-Seeded Rice (DSR) from traditional puddled transplanted rice, aimed at saving water and labour, has triggered a weed explosion. *Echinochloa crusgalli, Echinochloa colona,* sedges like *Cyperus iria,* and broadleaf weeds such as *Eclipta alba* are important weeds in rice. Weedy rice is the most serious challenge in DSR systems. It closely resembles cultivated rice but competes aggressively, contaminating harvests and reducing grain quality.

Wheat: The notorious weed in wheat is *Phalaris minor*, a grassy weed that looks almost identical to wheat at early growth stages. Due to the repeated use of the same herbicides, it has developed resistance. Weeds like *Chenopodium album* and *Melilotus alba* are also widely reported.

Maize: In maize, weeds germinate quickly after sowing and are particularly competitive during the first 30 days. Common weeds include *Amaranthus viridis, Trianthema portulacastrum,* and grassy weeds such as *Echinochloa colona.*

Soybean: Soybean is highly sensitive to weed pressure in the early growth stages. *Parthenium hysterophorus, Euphorbia hirta,* and grassy weeds dominate fields.

Cotton: Cotton is particularly vulnerable to weeds during the first 6–8 weeks after sowing. Weeds like *Cyperus rotundus, Trianthema portulacastrum*, and several grasses compete aggressively.

Emerging challenges in weed management

Climate change is shifting weed populations,

Pusa Basmati 1985

SAVA 134 FP

favouring heat- and drought-tolerant species like *Parthenium hysterophorus.* Overuse of a few herbicides has triggered resistance, as seen in *Phalaris minor* in wheat, forcing costlier, complex mixes. Weed mimicry, such as weedy rice in DSR and *Phalaris minor* in wheat, complicates identification. Labour shortages and rising wages make manual weeding unaffordable, with weeding costs reaching 25% of total cultivation expenses. Indiscriminate herbicide use harms soil microflora, contaminates water, and threatens non-target species. Addressing these challenges requires precision herbicide use, diversified strategies, and integration with non-chemical methods for sustainable weed management.

Herbicide-tolerant crops: Science and development

Herbicide-tolerant crops are defined as genetically modified plants engineered either to reduce the sensitivity of certain enzymes to herbicides or to include pathways that detoxify herbicides, enabling them to survive specific herbicide applications without damage. HT crops provide farmers with an essential tool to combat weeds and are compatible with no-till methods, which help preserve topsoil. They give farmers the flexibility to apply herbicides only when necessary, control the total input of herbicides, and select herbicides with desirable environmental characteristics. Non-selective herbicides like glyphosate and glufosinate help broaden the range of weeds controlled, which is especially important in no-till systems and farmers sow an HT crop, when weeds emerge, they spray a broad-spectrum herbicide, and weeds die, but the crop survives unharmed. This makes weed control easier, faster and more reliable, especially during the critical early stages of crop growth.

Mechanisms of herbicide tolerance

- ***Target-site modification:*** Mutations in herbicide target enzymes prevent binding (e.g. ALS/AHAS mutation in HT rice for imidazolinone tolerance).
- ***Metabolic detoxification:*** Added genes produce enzymes that deactivate herbicides (e.g. bar/pat gene detoxifies glufosinate).
- ***Overexpression of target enzyme:*** Crops produce excess target enzymes, reducing herbicide sensitivity (e.g. CP4-EPSPS gene in glyphosate-tolerant crops).
- ***Physiological/structural traits:*** Traits like thicker cuticles, reduced absorption, or faster herbicide breakdown limit damage.

Herbicide-tolerant crop development

Conventional/Mutation breeding: Induce mutations to find tolerant plants, then cross with high-yielding varieties (e.g. Clearfield® rice). In India, CR Dhan 807, Pusa Basmati 1979, and Pusa Basmati 1985 are non-GM rice tolerant varieties to imazethapyr.

Transgenic approaches: Introduce foreign genes for tolerance (e.g. CP4-EPSPS for glyphosate, bar/pat for glufosinate, DMO for dicamba). Widely adopted in the USA, Brazil, and Canada.

Genome editing (CRISPR-Cas9): Precisely edits

MTU 1010 Imazethapyr sprayed

CRR Dhan 807

Sava 127 FP hybrid rice

Pusa Basmati 1979

DNA without adding foreign genes (e.g. ALS gene editing for imidazolinone-tolerant rice or wheat). Faster, precise, and less controversial than transgenics.

Global adoption of HT crops

HT crops are widely adopted worldwide. Over 90% of U.S. soybean and maize, nearly all Brazilian soybean and cotton, and most Canadian canola are HT. In Asia, countries like Vietnam, the Philippines, and India grow HT rice. Their global success shows HT crops significantly cut weeding costs and labour while boosting productivity.

Table 1. Major herbicide-tolerant crop systems

Crop	Herbicide	Mode of action	Benefit	Concern
Soybean, maize, cotton, canola	Glyphosate	Inhibits EPSPS enzyme	Effective, broad-spectrum and relatively safe herbicide	Overuse has led to glyphosate-resistant weeds (e.g. *Amaranthus palmeri)*
Canola, maize, soybean, cotton	Glufosinate	Inhibit glutamine synthase enzyme in plant	Effective against glyphosate-resistant weeds	Slightly more expensive; requires precise application
Rice, maize, wheat, sunflower	Imidazolinone	InhibitALS/ AHAS enzyme	Non-GM, accepted in many countries	Rapid development of resistant weeds if misused
Soybean, cotton	Dicamba and 2,4-D	Synthetic auxin	Effective on broadleaf weeds resistant to glyphosate	Risk of herbicide drift damaging sensitive crops

Advantages of non-GM HT crops for India

India remains cautious about GM crops. Non-GM HT varieties like Pusa Basmati 1979, Pusa Basmati 1985, and CR Dhan 807 rice offer a safer entry as they avoid regulatory and export hurdles, can be bred conventionally or via mutation, and are more acceptable to farmers and consumers.

Why HT crops must be used with stewardship?

HT crops are valuable but not fool proof. Over-reliance on one herbicide can cause resistance, as seen with weedy rice in Clearfield® systems, a real risk for India's direct-seeded rice and wheat. Stewardship is vital, it rotate herbicides with different modes of action, avoid continuous use, integrate cultural methods like stale seedbeds, crop rotation, mulching, and mechanical weeding, and educate farmers through Krishi Vigyan Kendras and Farmer Producer Organizations.

Global experience

Herbicide-tolerant crops' three-decade history offers India both promise and caution.

- ***USA:*** >90% of soybean, maize, and cotton are HT, boosting yields and no-till farming. Overuse of glyphosate bred resistant weeds (*Amaranthus palmeri*), prompting costly mixtures and tillage, showing the need for herbicide rotation and IWM.
- ***Brazil:*** Nearly all soybean is HT, lowering costs but causing resistant weeds *(Conyza, Digitaria)*.
- ***Canada:*** 95% HT canola success stems from multiple HT systems and strong stewardship.
- ***Asia:*** Clearfield® rice controls weedy rice but bred resistant strains, thus rotation is vital.
- ***U.S. Dicamba drift:*** Off-target damage caused disputes, spray management matters.
- ***Australia:*** Integrated strategies slowed resistance development.

HT crops bring major gains (weed control, yield and labour) but need multiple systems, farmer education, regulation, drift control, and IWM for long-term sustainability.

Current status of herbicide-tolerant crops in India

India, a major agrarian economy, remains cautious with HT-crops, unlike the U.S. or Brazil where HT crops dominate. Labour shortages, water stress, and rising weed resistance are driving renewed interest.

- ***Officially released HT crops:*** Non-GM HT rice is the only approved HT crop, like Pusa Basmati 1979, Pusa Basmati 1985, and CR Dhan 807 tolerate imazethapyr, reflecting India's preference for non-GM options.
- ***HT mustard (DMH-11):*** A GM mustard hybrid tolerant to glufosinate, approved by GEAC in 2022, faces legal challenges. A 2024 Supreme Court split verdict directed creation of a national GM policy, leaving its future uncertain.
- ***HT cotton:*** Unapproved HT *Bt* cotton is grown illegally in several states. Farmers adopt it for easy weeding despite quality and legal risks,

underscoring demand for HT solutions and regulatory delays pushing grey-market adoption.

- ***Policy and regulatory framework:*** India's regulation of HT crops is cautious. Non-GM varieties like CR Dhan 807 and Pusa Basmati 1979/1985 face fewer hurdles, while GM HT crops encounter opposition over biosafety, biodiversity, and trade. In 2022, glyphosate use was restricted to licensed Pest Control Operators, limiting farmer access. This reflects a precautionary approach balancing HT crop potential with environmental and social concerns.
- ***Role of research institutions:*** ICAR, SAUs, and the seed industry are progressing with HT crop research. ICAR-CRRI released CR Dhan 807 for direct-seeded rice; ICAR-IARI released Pusa Basmati 1979 and 1985; Delhi University developed GM mustard hybrid DMH-11; SAUs are developing HT maize and soybean and are currently under trials. The Seed Industry (SAVANNAH Seeds) released SAVA 127 and SAVA 134 with Fullpage technology; others are working on developing HT varieties.This reflects India's dual approach: Non-GM HT crops for faster adoption and GM/genome-edited crops for long-term innovation.
- ***Farmer demand for HT crops:*** Farmer behaviour clearly shows strong demand for HT technology, as labour shortages and high weeding costs make HT crops attractive. Farmers growing cotton, rice, and soybean are especially keen on HT options, and many have even self-adopted illegal HT Bt cotton despite regulatory risks, proving that practicality often outweighs policy restrictions.
- ***Opportunities and risks for India:*** HT rice can boost DSR by saving water and labour; HT mustard may cut edible oil imports through higher yields; HT cotton and soybean can reduce labour needs and costs are some opportunities. While overuse of single herbicides may cause resistant weeds, environmental issues like drift and soil residue, public resistance to GM crops, and legal risks for unapproved HT crop cultivation are possible risks.
- ***Integrated weed management with HT Crops:*** India must avoid past global mistakes of rapid herbicide resistance. HT crops should be integrated into IWM, using crop and herbicide rotation, stale seedbeds, mechanical and cultural controls, and farmer training via KVKs and FPOs to ensure sustainable weed management.

Benefits of herbicide-tolerant crops for farmers

- ***Labour savings:*** 10–15 days/ha, reducing dependence on scarce workers.
- ***Cost reduction:*** Weeding costs drop from ₹ 4,000–6,000/ha to ₹ 800–1,200/ha.
- ***Timely, broad-spectrum control:*** Protects crops during the critical 30–40 days after sowing.
- ***Reduced crop injury and higher yields:*** CR Dhan 807 showed 15–20% yield gains under DSR.
- ***Supports conservation agriculture:*** Enables zero-tillage and residue retention.
- ***Smallholder flexibility:*** Backpack sprayers suffice.
- ***Low soil residue:*** Glyphosate and glufosinate minimize carry-over.
- ***Gender benefits:*** Lessens women's weeding drudgery.
- ***Higher incomes:*** Adds ₹ 5,000–8,000/ha for cotton and rice farmers.

Risks, concerns, and stewardship needs

- ***Herbicide resistance:*** Possible in HT rice if imazethapyr is overused.
- ***Gene flow:*** Tolerance genes may spread to wild relatives or conventional crops.
- ***Environmental impacts:*** Soil health, biodiversity, and water contamination concerns.
- ***Spray drift:*** A concern for fragmented farms.
- ***Increased herbicide use:*** Resistance may require higher doses or multiple herbicides.
- ***Legal risks:*** Only Pusa Basmati 1979, 1985, CR Dhan 807, SAVA 127, and SAVA 134 FP are approved (as of July 2025).
- ***Awareness gaps:*** Misuse of doses, timing, and safety gear.
- ***Socio-economic issues:*** Dependence on seed firms and unequal benefits.
- ***Shared responsibility:*** Requires stewardship by all stakeholders.

Future prospects and recommendations

- ***Expand HT rice:*** Develop region-specific and basmati lines.
- ***Strengthen mustard research:*** Use transparent communication to build trust.
- ***Explore HT soybean and maize:*** Suitable for central India and mechanized farming.
- ***Ensure legal seed systems:*** Prevent illegal, poor-quality seeds.
- ***Promote IWM:*** Rotate crops/herbicides, use mixtures, manage volunteers, and integrate mechanical methods.
- ***Farmer training:*** Use KVKs, FPOs, and digital platforms.
- ***Policy clarity:*** Adopt science-based, transparent regulations balancing innovation and safety.

SUMMARY

Weeds silently threaten Indian agriculture, while HT crops provide modern solutions to reduce labour, cut costs, and boost yields. However, misuse can lead to resistant weeds, environmental problems, and social conflicts. The success of HT crops in India depends on responsible stewardship, integration into weed control strategies, effective regulation, and farmer awareness. When combined with water-saving practices like DSR and conservation agriculture, HT crops can lessen drudgery, increase profitability, and enhance long-term food and nutritional security especially under supportive policies and comprehensive extension services.

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Sugarcane+maize intercropping:

A next-generation approach to achieve food-energy-water security and biofuel self-reliance in India

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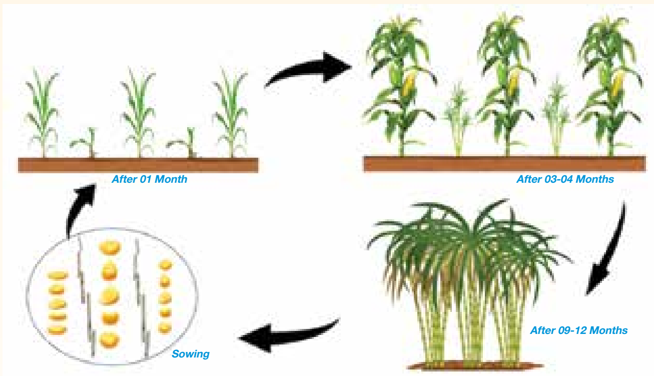
Monoculture of sugarcane in India is causing inefficient resource utilization and delayed economic returns. To overcome these limitations, sugarcane+maize (SM) intercropping system has emerged as a sustainable and profitable alternative. The system strategically integrates maize during sugarcane's initial slow growth phase, thereby improving land and water use efficiency while ensuring an additional income to farmers. Maize, with its short growth cycle, complements sugarcane by utilizing otherwise underutilized resources and diversifying farm output. Beyond food and feed, maize grain also serves as a potential feedstock for dual-feed distilleries, thereby supporting India's bioethanol production targets. Recent on-farm field demonstrations have showed that SM intercropping increases sugarcane equivalent yield (SEY) by approximately 28% over sole sugarcane (150 t/ha) and translating into significantly higher net profits (₹ 1,25,000/ha). The maize yield of 4–8 t/ha was achieved in various agroecologies in SM system. The SM system has the potential to expand on to 15 lakh hectares which can produce more than 60 lakh tonnes of maize. SM intercropping also helps in strengthening biofuel security in India.

Keywords: Bioethanol production, Profitability, Resource use efficiency, Sugarcane-maize intercropping

SUGARCANE (*Saccharum officinarum* L.) is one of India's most important commercial crops. However, growing it as a sole crop poses several challenges including inefficient resource utilization during its slow initial growth, high water demand, and delayed economic returns due to its long cropping duration. Moreover, the sugarcane crop gives income to the farmers after almost 10–15 months which may pose a hardship to the farmers in managing their daily expenses. Mono-cropping of sugarcane increases vulnerability to pests and diseases, further impacting productivity, profitability, resource use efficiency, and overall sustainability. Additionally, the water-intensive nature of sugarcane cultivation exacerbates pressure on already limited water resources in many regions of India. The crop ecosystem further suffers due to the non-functioning of its industries around the year. Recently, the Government of India's initiative and support for clean fuel led to the intallation of dual feed-based ethanol producing plants in sugarcane areas. In these dual-feed distillaries, apart from sugarcane and it's byproduct (molasses) grains primarily maize is being utilized to produce bioethanol which is being used in the belended petrol programme of the Government. Therefore, these distilleries are becoming increasingly important for the overall sustainability of sugarcane



Crop cycle of sugarcane and maize crops in sugarcane+maize intercropping system

Sugarcane and maize crops at tasselling and cob formation stages in sugarcane + maize intercropping system in Solapur, Maharashtra

ecosytems in the country. However, the non-availability of the maize grain for feedstock is a serious challenge as there is not enough area for growing the crop nearby sugar industries.

To overcome these limitations, intercropping sugarcane with short-duration crops like maize (*Zea mays* L.) could be a promising strategy to enhance resource (land and water) use efficiency, improve soil health, and provide supplementary income to farmers. The maize can mature in 90–120 days and can efficiently utilize the initial slow growth period resources used in sugarcane cultivation. Hence, the intial period of slow growth in sugarcane can be effectively used for cultivation of maize as an intercrop. Research at ICAR-IISR indicated the green cob harvesting potetail for sugarcne + maize intercropping system. As this is going to be a new system for grain prodcution, broad guidelines on its cultivation are provided in this article based on the available lietarure and on-farm studies in vaious agro-ecologies in India.

Management practices for sugarcane+maize intercropping

Climatic requirements: Sugarcane is best suited to tropical climates, but can also be successfully grown in sub-tropical areas. Maize, on the other hand, thrives in temperatures ranging from 9–46°C with the optimum temperature around 34°C. However, exposure to temperatures exceeding 32°C, as well as frost, can diminish yield during the reproductive period. The ideal soil temperature for germination and seedling growth is 26–30°C. The sugarcane is planted in southern India in July/August or the rainy season while the spring season planting of sugarcane in northern India can be successfully intercropped with maize.

Soil type: Sugarcane and maize crops exhibit adaptability to a wide range of soil types, from sandy loam to clay loam, making them versatile for cultivation under diverse agro-climatic conditions. However, maize is highly sensitive to waterlogging and water scarcity, necessitating precise water management for optimal growth and productivity. On the other hand, soils with high organic matter content, high water-holding capacity, and a neutral pH (6.5-7.5) are ideal for more productive growth of both crops.

Cultural practices

Sowing time: In northern India, mid-February to mid-March is the optimum time for planting sugarcane which aligns well with the ideal sowing time for spring maize across different agroecological regions of India. In southern India, anytime sowed sugarcane can have maize as intercrop. However, in the ratoon sugarcane crop, maize can be plated just after harvesting the planted sugarcane crop throughout India.

Method of sowing and spacing: Sugarcane should be planted in rows 75–100 cm apart and 20–25 cm deep trenches. After placing the setts in trenches, cover them with 5 cm of soil. Maize should be sown simultaneously on the ridges of sugarcane with 25–30 cm plant spacing. Apply irrigation immediately after planting, if planting is not done under sufficient moisture (Vattar) conditions. The paired row planting of sugarcane (75:150 cm) interval facilitates better intercropping opportunities. In this, two rows of maize can be placed in 150 cm space available.

Seed rate: Use 50,000 three-budded setts or 37,500 four-budded sets or 30,000 five-budded setts per hectare of sugarcane. For manual sowing of maize by hand, the seed rate varied between 12–15 kg/ha. However, the seed rates of maize of 12 kg/ha when using a hand-push plant seeder is sufficient.

Seed treatment: To promote sugarcane germination, it is recommended to soak the setts in an Ethrel 39 SL solution, using 25 ml of the product dissolved in 100 L of water for 24 h before planting. For maize, the seeds should ideally be pre-treated but if required, then applied Imidacloprid @4 g/kg of maize seed or a combination of Cyantraniliprole 19.8% + Thiamethoxam 19.8% FS @6 g/kg of seed to protect against fall armyworm infestations. However, maize hybrid seed bought in market mostly treated, if produced by own, the seed treatment is required.

Detopping and *in situ* drying of cob for quality production in sugarcane + maize intercropping system

Nutrient management

At the time of planting, apply a full dose of phosphorus (P_2O_5) and potassium recommended for sugarcane. The recommended nitrogen in sugarcane be applied as one-third at planting, and the remaining two-thirds in equal splits during the tillering and grand growth stages. In addition to this, for maize, N should be applied at 100 kg/ha, which is divided into two equal splits at knee-high and tasselling stages near the root zone of maize plants. For this, apply 1 bag (45 kg) of urea/acre each at knee-high and tasselling stages.

Water management

Applying irrigation for sugarcane and maize in the ridge and furrow system would be ideal where water is applied in furrows up to a third of the height of ridges or beds. Most of the time, the irrigation schedule of the sugarcane be followed for sugarcane + maize intercropping system. The moisture-sensitive stages of maize i.e. seedling, knee high, silking, and grain filling should be assured moisture if it is not twinning with the sugarcane schedule. The use of drip irrigation system can improve performance and yield of SM system further.

Weed management

- ***Manual weeding:*** Perform two to three hoeing operations using a hand-operated rotary weeder to manage weeds in the intercropping system.
- ***Chemical control:*** Effective weed control involves timely herbicide application during various crop growth stages. The percentage of yield losses in maize ranges from 25–80%, and is greatly influenced by the type of weeds present, duration of the crop-weed competition, and the density of weeds.

Table 1. Recommended herbicides for sugarcane+maize intercropping system

Herbicide Name	Type	Dose (a.i. g/kg per ha)	Formulation (g/ml/kg/L per ha)	Dilution in Water (L)
Atrazine 50% WP	Pre-emergence	500–1000	1000–2000	500–700
Topramezone 10 g/L + Atrazine 300 g/L SC	Post-emergence	766	2500	500
Halosulfuron Methyl 75% WG	Post-emergence	67	90	375
Mesotrione 2.27% w/w + Atrazine 22.7% w/w SC	Post-emergence	865	3460	500

Pest and disease management

Effective pest management is equally crucial for maintaining the overall health of the crops and ensuring optimal yields. Apply Azoxystrobin 18.2% + Difenoconazole 11.4% w/w SC at a concentration of 0.03% (0.3 g/L) or with a formulation of 0.1% (1 ml/L water) to control blight and downy mildew in maize, as well as red rot, smut, and rust in sugarcane.

Table 2. Recommended insecticides for sugarcane+maize intercropping system till harvest of maize

Insecticide Name	Dose (a.i. g/ha)	Formulation (g or ml/ha)	Dilution in Water (L)	Insect-pest
Chlorantraniliprole 18.50 % SC	37	2000	500	Fall armyworm and borers
Flubendiamide 2 20 % WG	50	250	500	

Handling and processing of maize

- ***Harvesting:*** In intercropping systems, maize is typically harvested first to avoid interference with the growth and development of sugarcane. The maize cobs should be harvested when the grains reach physiological maturity, which is usually marked by the formation of a black layer at the base of the kernel. Cut the remaining green maize stalks at ground level and use them as animal fodder.
- ***Threshing:*** After harvesting, the next step is to separate the kernels from the cobs using mechanical maize shellers or threshers for efficiency. Once the kernels are removed, it is crucial to ensure proper drying of the grains to reduce their moisture content to 12–14%. This moisture range is ideal for safe storage and prevents issues like mild growth, insect infestations, or spoilage during storage.

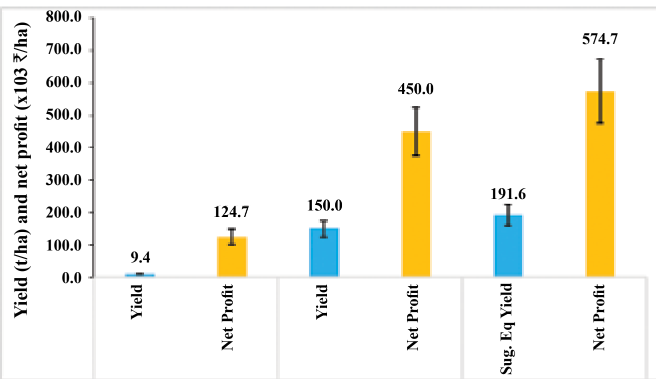
Crop yield and profitability

The on-farm demonstrations were done at the farmers' fields in Solapur Maharashtra in *khairf* and *rabi* season. Sugarcane+maize (SM) intercropping recorded the highest net profit of ₹575 x 10^3 ₹/ha, which is 125 x 10^3 ₹/ha higher than sugarcane sole, and saved ₹ 1,01,000–₹1,48,000/ha. In terms of yield, SM intercropping (~192 t/ha) achieved ~28% more sugarcane equivalent yield (SEY) than sugarcane sole (150 t/ha). Therefore, a significant economic advantage of SM Intercropping over sugarcane monocropping system, making it a more productive and profitable option for farmers. The farmer harvested 4–7 t/ha.

Sugarcane+maize intercropping system was demonstrated in 50 acres by Indian Institute of Maize Research (IIMR). This system is being expanded from Maharashtra to Haryana, and Eastern and Western Uttar Pradesh during the spring 2025. Farmers harvested 4–7 t/ha of maize in *kharif/rabi* season in Solapur. The maize income covered the entire cost of sugarcane cultivation comfortably. In spring planted sugarcane, farmers harvested impressive maize yield of 5–7 t/ha.

Key Interventions of SM intercropping system

- ***Deploy simplified crop management:*** Common weed and pest management and synchronized reduced labour, input cost, and improved system efficiency.



Crop yield and net profit of sole maize and sugarcane, and their intercropping

Sugarcane + maize intercropping system Bulanshahr, Uttar Pradesh

- ***Short to medium duration hybrid:*** High-yielding, short/medium-duration maize hybrids ensured compatibility with sugarcane and stable yields across ecology to be taken. The maize crop to be detopped or harvested before active tillering stage. Green cob purpose maize to be taken, its duration is longer to avoid adverse effect on sugarcane.
- ***Resource-efficient intercropping:*** Maize cultivated during the first 3 months of sugarcane with 50–75% plant stand (20–25 thousand/acre), synchronized water management, and additional 2 urea bags/acre as top dressing maximized the efficiency.
- ***Detopping and green fodder use of maize:*** The detopping of maize done at 70–90 days (at brown husk) and green fodder can be fed to animal; it will have better insolation for sugarcane. The cob will be dried *in situ* for better grain quality.
- ***Sustainability and profitability:*** Reduced inputs, higher resilience, and dual-feed ethanol support improved farmer income and timely payments.
- ***Scalability:*** The SM model has potential to expand on to 15 lakh hectares of yearly planted sugarcane (1/3rd acreage) and can produce >60 lakh tonnes of maize especially for dual feed ethanol industries. It will increase farmer profitability and resource use efficiency for sustainable sugarcane production.

SUMMARY

Sugarcane+maize intercropping system optimizes land and water use, boosts farmer income, and supports bioethanol production. By efficiently utilizing sugarcane's slow initial growth phase, maize enhances soil health and reduces weed pressure. This system increases farm profitability, promotes sustainability, and strengthens India's clean fuel initiative, making it a viable solution for future agriculture.

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Advanced seed multiplication and planting techniques for sustainable sugarcane

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Sugarcane is an important industrial crop for sugar and ethanol production, but its conventional propagation through three-bud setts is bulky, costly, and prone to disease transmission. Advanced seed multiplication methods such as tissue culture, bud chip, cane node, and spaced transplanting address these challenges by reducing seed requirement, ensuring disease-free planting material, and enhancing rapid varietal replacement. Combined with improved planting techniques like trench, FIRB, and ring pit method, these innovations increase productivity, resource efficiency, mechanization, and sustainability in sugarcane cultivation.

Keywords: Bud Chip, Seed multiplication, Sugarcane, Tissue culture

SUGARCANE (*Saccharum officinarum x spontaneum* L.) is a versatile crop primarily used for sugar production. Furthermore, its role has extended to being a vital raw material for ethanol generation. Traditionally, sugarcane is propagated through three bud setts in a conventional system. Nonetheless, this approach presents intricate challenges in seed production, along with the cumbersome processes of transportation, exchange, and replacement. These difficulties arise from the reliance on vegetative propagation and the substantial quantities of planting material required. One of the major expenses in sugarcane production is the seed cane, which is required in substantial quantities. In the conventional propagation system through sett cutting, the seed multiplication ratio is about 1:10, meaning 1 hectare of seed crop yields enough seed cane to cover 10 hectares. A good seed cane should be healthy, free from pests and diseases, with high moisture content and rich reserves of invert sugars and soluble nitrogen compounds. Choosing seed cane with these qualities is essential for ensuring strong germination and high productivity in sugarcane.

For replacing old, deteriorated, or de-notified varieties with improved ones, a well-structured seed production chain is required. Since new varieties demand quick dissemination, rapid multiplication methods such as bud chip, cane node, and tissue culture techniques are commonly employed to accelerate their replacement. To fully harness the potential of newly evolved sugarcane varieties, it is essential to deploy them in suitable niches. Early maturing varieties like CoLk 14201, CoLk 16202, CoLk 15466, CoLk 15201, Co 15023 and CoS 13235 are gaining popularity among farmers and may replace red rot susceptible varieties. The introduction of new seed multiplication methods can reduce the bulkiness of seeds and make transportation easier. Using genetically pure and disease-free seed cane alone is expected to improve stalk yield by 10–15%. Quality seeds are essential for realizing the full benefits of other inputs such as manures, fertilizers, water, land, and labour. The cost of seed cane and the quantity of seed material required for planting account for approximately 20% of the total cultivation cost. By using bud chip settlings along with improved production technology for nursery management, transplanting methods and timing, plant spacing, weed control, nutrient requirements, irrigation scheduling, and optimum time for cane harvesting, farmers can achieve a good cane yield of 100 t/ha. Adopting the bud chip method of sugarcane cultivation can save nearly 80% of the stalk material used for planting, which can be utilized for other purposes like consumption. The budchip technology has shown promising results, providing higher cane yield compared to the conventional method of planting with three-bud setts. The bud chip technology resulted in a 13.86% higher cane yield over the conventional method. The cane-node method is an innovative approach designed for the priming of sugarcane seed material, along with its systematic packaging, transport, certification, and placement in the field. This technique ensures rapid germination and contributes to higher cane yields. In this method, a small stem section containing a single bud, the root band, and about an inch of internode on either side is used as the planting material.

The adoption of innovative seed multiplication methods, coupled with the integration of refined production technologies for improved new sugarcane varieties can significantly enhance seed production and seed yield. Such advancements stand to significantly enhance the overall productivity and sustainability of sugarcane cultivation.

Major problems in conventional sugarcane seed production system

- ***Low seed multiplication rate:*** Conventional sugarcane seed production relies on the vegetative propagation of sugarcane through stem cuttings, resulting in a relatively slow multiplication rate. New methods that can accelerate seed multiplication could significantly increase the availability of planting material and lead to the more rapid establishment of new sugarcane crops.
- ***Disease transmission:*** Conventional seed multiplication methods may contribute to the spread of diseases, as pathogens can be transmitted through infected planting material. Developing new techniques that ensure disease-free planting material is crucial in maintaining healthy sugarcane crops and preventing widespread disease outbreaks.
- ***Space and labour-intensive:*** Conventional sugarcane seed production often requires large areas of land and significant labour inputs for planting, maintenance, and harvesting of the crop. Novel approaches that utilize alternative growth substrates, automated systems, or tissue culture techniques could help reduce space and labour requirements while increasing efficiency.
- ***Inefficient use of resources:*** Current seed multiplication systems might be inefficient in terms of water and nutrient use. New methods that optimize resource utilization and minimize waste could lead to more sustainable and environmentally friendly sugarcane production.
- ***Lengthy production cycle:*** Traditional seed multiplication techniques often have long production cycles before the sugarcane is ready for commercial planting. Shortening the multiplication cycle through innovative methods could help meet the increasing demand for sugarcane and accelerate the release of new improved varieties.
- ***Limited access to quality planting material:*** In some regions, farmers may face challenges in accessing high-quality sugarcane planting material due to limited availability. Introducing new seed multiplication techniques that can be easily adopted at the farm level could enhance accessibility and affordability for small-scale farmers.

Adopting new seed multiplication methods can address the major gaps in conventional sugarcane seed production, leading to more efficient, disease-resistant, and climate-resilient sugarcane crops.

Bud chip technology

Advance seed multiplication methods

- ***Tissue culture (micropropagation):*** Tissue culture produces plantlets from meristematic tissues or nodal segments under aseptic laboratory conditions. To lower costs for smallholder supply chains, many programmes use tissue culture to produce foundation material that is then multiplied using field-level methods (single-bud planting, nurseries). Its advantages are: 1) Produces pathogen-free plantlets (meristem-tip cultures eliminate systemic viruses and many bacteria/fungi), 2) Extremely high multiplication rates (one explant can yield thousands of plantlets within months), 3) Enables purification of elite clones and rapid propagation of newly released varieties.
- ***Bud chip technology:*** Bud chip technology (also called Single-bud propagation) plants one bud per unit instead of traditional 2–3 bud setts. Bud chips are cut from healthy, disease-free cane through bud chip cutter, treated (fungicide/insecticide), and planted in sterile media in trays or polybags. After 6–8 weeks, once shoots and roots develop seedlings are hardened and transplanted. Its advantages are: 1) Reduces seed requirement by up to 60–80% compared with conventional setts, 2) Promotes rapid expansion of a nucleus area of high-quality planting material, 3) Works well with nursery-based raising (polybag/tray systems) and transplanting.
- ***Cane node technology:*** In this technique, a cane node containing a healthy bud is selected and placed in a slurry made from decomposed farmyard manure (FYM) maintained at about 60% moisture. The


Cane node technology

Seedlings ready for STP

nodes are incubated in this medium for 4–5 days inside a container, during which the buds begin to sprout. Once sprouting occurs, the germinated buds are carefully transported to the field and planted in furrows. This approach promotes rapid and uniform bud sprouting, ensures convenient handling and transport of planting material, and reduces the bulkiness of seed cane. Using the cane-node method, only about 1–2 tonnes of seed material are required to plant one hectare, making it far more efficient than conventional seed cane usage.

- ***Space transplanting technique (STP):*** Spaced transplanting in sugarcane involves raising seedlings from single-bud setts or bud chips in a nursery for 25–35 days and then transplanting them into the main field at wider spacing (90×90 cm or 120×60 cm). This method saves seed material (1–1.5 tonnes vs. 6–8 tonnes in conventional planting), ensures uniform crop stand, promotes better tillering, facilitates intercropping and mechanization, and reduces pest/disease incidence. Though it requires initial nursery management and careful transplanting, it enhances productivity and efficiency.

Table 1. Seed multiplication through advanced seed multiplication method

Planting techniques	Conventional Method	STP (Space transplanting)	Bud chip	Cane node technology
Seed requirement (q/ha)	60–70	20	8–10	8–10
Seed multiplication ratio	1:10	1.40	1:60	1:60
Initial Investment: 4–5 lakhs				
Profit: 10–15 lakhs per season (80 paisa to 1 ₹ investment for per plantlet and 4–5 ₹/plantlet gain)				
• Sugarcane conventional cultivation: 1.5 lakh profit				
• Seed production: 3–4 lakh				

Planting techniques

The method of planting should be designed to promote extensive root growth and penetration into the soil profile, allowing the crop to make optimal use of available nutrients and moisture for better productivity. To reduce labour intensity in field operations particularly harvesting and intercultural practices, wider row spacing is advised. It the sub-tropical zone, row spacing of 120 cm or 30:150 cm is recommended to enable mechanized harvesting while sustaining high cane yields. In tropical regions, a spacing range of 120–150 cm proves more suitable, as it supports mechanization and ensures good yield levels.

- ***Flat planting:*** It is the most common and traditional method of planting, mainly practiced in areas with adequate irrigation. In this technique, well-prepared and leveled fields are used, and furrows are opened about 8–10 cm deep. Healthy cane setts of two or three buds are placed horizontally in the furrows, end to end, and then covered with soil. Row spacing is generally 75 cm. This method is simple, requires less labour, and ensures quick and uniform germination.
- ***Trench method:*** The trench method of planting is recommended to achieve higher yields in both plant and ratoon sugarcane crops. This system helps prevent lodging and performs well even in light soils. The ICAR-ISRI, Lucknow has developed a mechanized version of trench planting with the key features: 1) Trenches are prepared 30 cm wide and 25–30 cm deep, 2) A spacing of 120 cm (90 cm + 30 cm) is maintained from center to center between two trenches, 3) A trench planter is used for mechanized sowing of sugarcane setts in a paired-row pattern.
- ***Furrow irrigated reduced bed planting:*** At IISR, an innovative Furrow Irrigated Raised Bed (FIRB) system has been developed to minimize cane yield reduction under late planting conditions. In this approach, 2–3 rows of wheat are sown on raised beds during October-November, while sugarcane is planted in the furrows at its optimum season of February-March. The recommended bed configuration is 50-30-50 cm. This method ensures that sugarcane receives sufficient time for tillering and grand growth, while both crops benefit from timely planting and an improved rhizosphere environment. As a result, the yields of wheat as well as sugarcane are enhanced.
- ***Ring pit planting (No-tiller technology):*** In this method, sugarcane tillering is minimized while encouraging the vigorous growth of mother shoots, resulting in a higher number of millable canes with greater length and weight. This approach, commonly referred to as "No-Tiller Technology",

FIRB method of planting

Ring pit method of planting

involves digging pits of 75–90 cm in diameter and about 30 cm deep using a mechanized pit digger.

Table 2. Planting techniques and their characteristics

Planting Techniques	Characteristics
Flat Planting	75 cm vide bed and shallow furrow of 8–10 cm deep
Trench planting	Trenches are prepared with a width of 30 cm and a depth of 25–30 cm A 120 cm spacing is maintained from center to center between trenches (configured as 90 cm:30 cm) Sugarcane setts are planted mechanically in a paired-row pattern using a trench planter
Ring pit planting	Pits of 75–90 cm in diameter and 30 cm deep are created using a mechanized pit digger. About 9,000 pits/ha (105 cm spacing) or 6,900 pits/ha (120 cm spacing) are prepared, maintaining center-to-center distances. The excavated soil is placed around the edges of each pit, and fifteen treated 2-bud setts are arranged inside each pit in a radial pattern, similar to the spokes of a wheel.
Furrow Irrigated Raised Bed (FIRB) technique	Wheat is sown in 2–3 rows on raised beds during October–November, while sugarcane is planted later in the furrows at its ideal planting time (February–March). The raised bed system follows a 50–30–50 cm configuration.

Depending on spacing, nearly 9000 pits/ha (at 105 cm spacing) or 6900 pits/ha (at 120 cm spacing) are created, with the excavated soil placed around the rim of each pit. For planting, 20 treated 2-bud or 3-bud setts are arranged radially inside each pit, resembling the spokes of a wheel. To promote healthy establishment, *Trichoderma* (20 kg/ha) mixed with 200 kg FYM or press mud is applied over the setts, along with the recommended dose of manures, fertilizers, and crop protection chemicals. During intercultural operations, the dug-out soil is gradually refilled into the pits up to a depth of 5–7 cm. This technique significantly improves resource efficiency enhancing cane yield by 1.5–2 times, increasing water use efficiency by 30–40%, and improving nutrient use efficiency by 30–35%.

SUMMARY

Adopting innovative seed multiplication and planting techniques ensures efficient resource use, rapid varietal replacement, and higher yields. These advancements lower costs, save seed material, enable mechanization, and support sustainable, profitable sugarcane cultivation.

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Custom hiring: The catalyst for inclusive farm mechanization and Viksit Bharat

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Farm mechanization provides multiple benefits. Custom hiring of farm mechanization is likely to benefit the farmers by reducing the capital burden, improving machine utilization, reducing per-unit costs, and ensures timely field operations with precision, particularly in rainfed agriculture. Climate-smart mechanization via custom hiring must become a central pillar of transformation in agriculture. This approach focuses on energy-efficient and low-emission technologies, precision farming tools for optimal resource use, and machinery that supports sustainable practices. In India, operationally sustainable and economically feasible custom hiring centres network, is likely to bridge the mechanization gap, enhance agricultural resilience, and move decisively towards the vision of a "Viksit Bharat".

Keywords: Custom hiring, Climate-smart mechanization, Farm mechanization

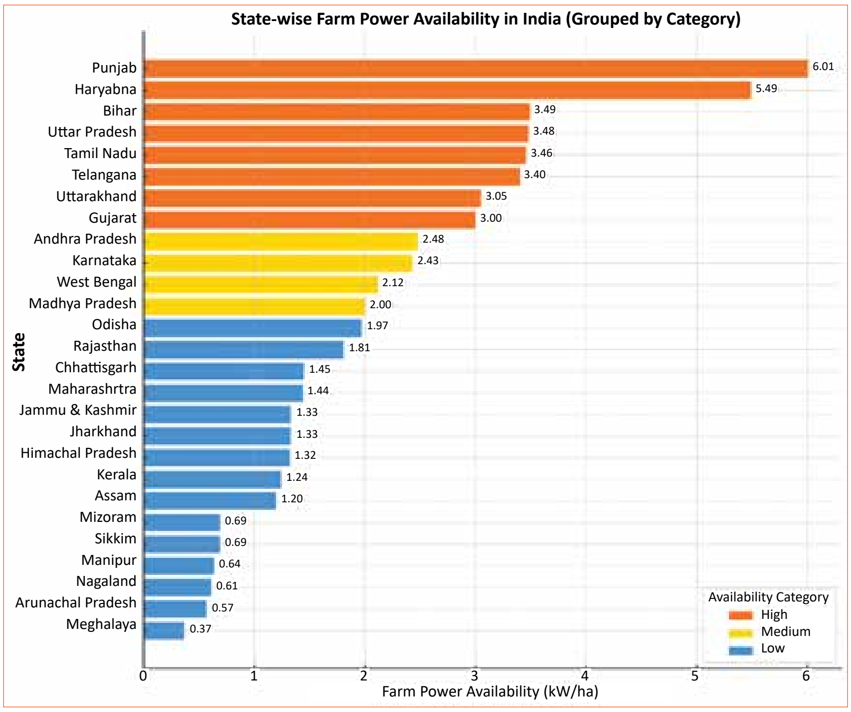
THE increased use of improved technologies in Indian agriculture since the mid-sixties has led to a multi-fold increase in agricultural production. Modern agriculture, with its growing reliance on commercial inputs, demands enhanced use-efficiency which is achievable only through timely and precise application using advanced agricultural machinery. This has amplified the need for higher levels of mechanization. Agriculture depends on seven vital inputs: Seed, fertilizer, irrigation water, plant protection chemicals, agro-machinery, transfer of knowledge, and credit. Among these, agro-machinery serves as the engineering backbone and its efficiency directly influences the effectiveness and precision of all other inputs. Mechanization enhances timeliness of operations, which is essential for maintaining crop cycles, improving productivity, and reducing losses. Mechanization brings tangible benefits to the field like:

- 15–20% savings in seeds and fertilizers through precision application
- 5–20% increase in cropping intensity, enabling multiple cropping
- 20–30% reduction in time and manual labour, helping address rural labour shortages
- 10–15% rise in overall farm productivity, contributing to food security and income growth

The cropping intensity in Indian agriculture increased from 120% in 1975–76 to 142% in 2021–22, corresponding with a significant increase in farm power availability from 0.36 kW/ha to 3.04 kW/ha during the same period. Notably, the net sown area per tractor declined from 487 ha/tractor in 1975–76 to just 15 ha/tractor in 2021–22, reflecting rapid proliferation of tractors and greater mechanization at smaller scales. India is now the world's largest manufacturer and exporter of tractors, with the market valued at USD 7.54 billion in 2020, expected to grow to USD 12.7 billion by 2030. Tractors alone make up nearly 80% of India's total farm machinery, with threshers and rotavators closely following.

With increasing cropping intensity, Indian farmers have steadily shifted from animate power to mechanical sources like tractors, power tillers, diesel engines, and electric motors. The availability of draught animal power has come down from 0.212 kW/ha in 1971–72 to 0.075 kW/ha in 2021-22, whereas, the power available from tractors, power tillers, diesel engines and electric motors has increased from 0.02 to 1.932, 0.001 to 0.020, 0.053 to 0.368 and 0.041 to 0.568 kW/ha, respectively during the same period. This progression signifies India's gradual but consistent movement towards modern mechanized agriculture. However, mechanization levels remain uneven across operations. Tasks demanding high power and low precision such as tillage, transport, water pumping, milling, and threshing, are more mechanized. Mid-level mechanization is seen in operations like seeding, spraying, and intercultural work. But areas requiring high precision and lower power, like transplanting, vegetable planting, and fruit harvesting, still lag behind.

Moreover, mechanization access is skewed by landholding patterns. Mechanical power is primarily utilized on large farms, whereas small and marginal farmers who own nearly 85% of operational holdings often cannot afford high-cost machines like tractors, laser levellers, and combine harvesters. The average landholding in India has declined significantly from 2.82 hectares in 1970–71 to 1.16 hectares in 2010–11. More recently, it further shrank from 1.08 hectares in 2016–17 to just 0.74 hectares in 2021–22, a 31% drop, further undermining the economic viability of individual machine ownership driven by factors such as rural-to-urban migration, low wages, aging farm workforce, and the seasonal nature of farm employment, which is expected to intensify in the coming years. In such a scenario, mechanization is no longer optional, it is imperative. This is where custom hiring emerges as a game-changing solution. By enabling small and marginal farmers to rent equipment on a need-basis, either from better-off neighbours or dedicated Custom Hiring Centres (CHCs), custom hiring ensures access without the burden of ownership. It enhances the efficiency and utilization of machines, making their operation more economically viable. In essence, it democratizes technology, allowing all farmers, regardless of land size, to benefit from mechanization.



Variations in farm power availability among different states of India
(*Source:* Standing committee on agricultural, animal husbandry, and food processing, 2022–23, Research and development in farm mechanization for small and marginal farmers in the country; https://sansad.in/getFile/lsscommittee/Agriculture)

Among the many strategic interventions to transform Indian agriculture and realize the vision of "Viksit Bharat" (Developed India), custom hiring of farm machinery stands out for its inclusiveness, scalability, and transformative potential. With farm mechanization still at only 47% in India, compared to 70% in countries like China and Brazil, unlocking access to mechanization for smallholders is not merely a policy goal, it is a national necessity.

The uneven landscape of mechanization in India

India has witnessed remarkable growth in agricultural production since the green revolution, significantly supported by increased use of inputs and mechanization. While this progress has boosted productivity, the spread of mechanization remains highly uneven, both regionally and across crop types. States like Punjab and Haryana have farm power availability upwards of 5 kW/ha, whereas in the north eastern states and hilly regions like Meghalaya, Nagal and, and Arunachal Pradesh, it hovers below 1 kW/ha.

This stark regional disparity reflects broader challenges in terrain, accessibility, and infrastructure. A similar divide exists across cropping systems. While cereal crops like wheat and rice have achieved mechanization levels of 50–60%, horticultural crops, pulses, oilseeds, and rainfed farming systems remain largely untouched by modern machinery. The lack of suitable, crop-specific mechanized solutions, coupled with terrain-specific needs, has left these sectors under-mechanized and inefficient. These disparities are rooted in structural constraints like

- Small and fragmented landholdings, making individual ownership of high-cost machines increasingly uneconomical.
- Low capital availability and limited access to institutional credit, especially for small farm holders.
- Inadequate rural infrastructure, particularly in remote and hilly regions.
- Lack of technical skills to operate and maintain complex machinery.

Furthermore, tractors and combines, while useful, often go underutilized with average use below 600 hours annually, against an economic viability threshold of 1,000 hours. This not only leads to financial losses for owners but also restricts the broader adoption of machinery in rural communities. Addressing this unevenness requires targeted interventions such as promoting custom hiring services, supporting region-specific mechanization technologies, and expanding infrastructure and capacity building programmes to ensure that the benefits of mechanization reach every corner of Indian agriculture.

Custom hiring: Empowering India's smallholder majority

In a country where over 82% of farmers operate on less than two hectares, access to farm machinery remains a persistent challenge. Custom hiring centres (CHCs) offer a practical, scalable, and inclusive solution

Crop	Mechanisation Level
 Wheat	69 %
 Rice	53 %
 Pulses	46 %
 Ollseed	41 %
 Cotton	39 %
 Sugarcane	36 %
 Sorghum	35 %

Crop-wise mechanization level of major crops in India (*Source:* Standing committee on agricultural, animal husbandry, and food processing, 2022-23, Research and development in farm mechanization for small and marginal farmers in the country; https://sansad.in/getFile/lsscommittee/Agriculture)

by enabling small and marginal farmers to rent tractors, transplanters, harvesters, drones, and other machinery on a pay-per-use basis, thus bypassing the high cost of ownership. Already, over 63.5% of Indian farmers rely on rented machinery, reflecting both the pressing need and growing acceptance of this model. Custom hiring unlocks multiple benefits as it reduces the capital burden, improves machine utilization, lowers per-unit costs, and ensures timely field operations, a critical advantage in rainfed agriculture where every day post-monsoon matters. With only 53% of arable land under irrigation, completing sowing and harvesting within narrow windows can mean the difference between success and failure.

Modern agriculture is rapidly evolving, with innovations such as AI-powered diagnostics, GPS-guided sowing, drone spraying, and sensor-based irrigation defining a new era of precision farming. However, the benefits of these technologies will remain out of reach for smallholders unless made accessible through shared rental ecosystems. Research on farm mechanization reveals that it can increase productivity by up to 30% and reduce input costs by 20%. It also contributes to sustainability and inclusivity reducing drudgery, promoting women's participation, encouraging residue management, and ensuring precise application of water, seed, and agrochemicals. As India works towards its net-zero emission target by 2070, climate-smart mechanization via custom hiring must become a central pillar of agricultural reform. This approach focuses on energy-efficient and low-emission technologies, precision farming tools for optimal resource use, and machinery that supports sustainable practices such as residue incorporation and conservation agriculture.

CHCs are also enabling mechanization in previously untouched areas like paddy transplantation, horticulture operations, and precision spraying especially through women-friendly, lightweight, and miniaturized equipment tailored to small and intercropped plots.

The policy push: A multi-scheme momentum

India's policy framework has progressively embraced custom hiring as a strategic enabler of equitable mechanization. Leading this push is the Sub-Mission on Agricultural Mechanization (SMAM), launched in 2014–15, which aims to increase farm power availability from 1.84 kW/ha (2013–14) to 4 kW/ha by 2030. The scheme provides up to 80% financial assistance to Farmers Producer Organizations (FPOs), cooperatives, and Panchayati Raj Institutions for setting up CHCs. Individual farmers receive subsidies of 40–50% for machine purchases. This has led to a 65% increase in farm power, reaching 3.04 kW/ha by 2022, and significantly broadened access to machinery through shared models.

Complementing this, the Rashtriya Krishi Vikas Yojana (RKVY) offers flexible, state-driven funding for CHCs and Farm Machinery Banks, encouraging cluster-based implementation for localized efficiency. The Promotion of Agricultural Mechanization for *In situ* Crop Residue Management scheme further addresses environmental concerns by supporting CHCs with 80% subsidy on equipment like Happy Seeder and Super Straw Management Systems, tackling stubble burning in north India and improving regional air quality. To promote mechanization in traditionally underserved regions, the Bringing Green Revolution to Eastern India (BGREI) programme initiated in 2010 by the Government of India provides 50% assistance for rice machinery, often deployed through CHCs to ensure timely planting and harvesting in low-irrigation zones. Digital integration is accelerating access. The Drone Didi Scheme (2023) plans to deploy 15,000 agricultural drones to Women Self-Help Groups (SHGs) by 2026, enabling custom services in precision spraying, field mapping, and crop monitoring. Similarly, the Mission for Integrated Development of Horticulture (MIDH) promotes horticulture-specific CHCs for mini-harvesters, fruit pruners, and cold-chain equipment through Centre-State cost-sharing (60:40).

To further streamline access to shared mechanization services, the Government of India has launched the FARMS (Farm Machinery Solutions) mobile application in 2023 which is a multi-language digital platform designed to empower farmers across the country. Developed under the aegis of the Department of Agriculture Cooperation and Farmers Welfare (DAC and FW), Ministry of Agriculture and Farmers Welfare (MoA and FW), the app facilitates custom hiring services without requiring access to a computer system. The FARMS app connects users with Farm Machinery Banks (FMBs), CHCs and Hi-tech hubs established under various central schemes. It not only simplifies the process of renting machinery but also enables individual farmers to offer their own equipment for hire, allowing them to generate additional income while ensuring optimal utilization of available resources.

Several state governments have also developed innovative approaches to enhance the reach and impact of custom hiring services. Tamil Nadu and Maharashtra have introduced mobile CHCs to provide access to remote and underserved regions. Odisha and Madhya Pradesh have promoted SHG-led and youth-led CHCs, fostering rural employment and empowering women entrepreneurs. Additionally, the integration of digital booking platforms now enables real-time equipment rentals and service tracking, significantly improving transparency, operational efficiency, and ease of access for farmers.

Strategy for inclusive mechanization

To unlock the full potential of custom hiring and extend mechanization to every corner of India, a '5A approach' is essential.

- ***Awareness:*** Strengthen outreach via mobile apps, Krishi Vigyan Kendras (KVKs), and local demonstration programmes.
- ***Availability:*** Encourage domestic manufacturing of compact, modular, and terrain-specific machines to reduce dependency on low-quality imports.
- ***Accessibility:*** Promote decentralized CHCs, mobile rental units, and digital platforms to ensure last-mile service delivery.
- ***Affordability:*** Introduce flexible rental models, affordable EMIs, and support financing for cooperatives and SHGs.
- ***Ability:*** Invest in farmer training for machine handling, drone operations, and digital data interpretation.

With over 2,800 agri-tech startups, India is well-positioned to build a robust, digital-first rental ecosystem. What's needed is policy coherence, regional customization, and strong public-private partnerships to scale the CHC model as a rural service revolution.

SUMMARY

Mechanization in India must go beyond technology i.e. it must be a tool for empowerment. Custom hiring democratizes access, turning expensive assets into shared resources and empowering smallholders with the tools they need to thrive. By building a smart, inclusive, and sustainable CHC network, India can bridge the mechanization gap, enhance agricultural resilience, and move decisively towards the vision of a "Viksit Bharat", where progress is not limited by land size and no farmer is left behind.

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Enhancing ecosystem services through sustainable agriculture

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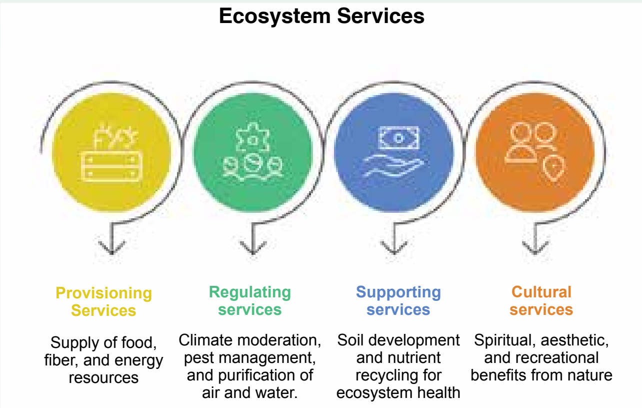
Sustainable agriculture enhances ecosystem services by improving soil health, conserving water, fostering biodiversity, and building climate resilience. Practices like agroforestry, conservation tillage, organic farming, and efficient irrigation promote carbon sequestration, reduce emissions, and secure food systems. Strengthening ecosystem services requires integrating climate-smart technologies, agroecological principles, and supportive policies. Investments in research, farmer training, and incentives such as payment for ecosystem services are vital. Bridging traditional knowledge with modern innovations, supported by strong policies and markets, will foster resilient landscapes, climate mitigation, and sustainable livelihoods.

Keywords: Crop diversification, Ecosystem services, Sustainable Agriculture

ECOSYSTEM services refer to the numerous benefits that humans derive from nature, and they are essential for both environmental health and agricultural productivity. These services are typically grouped into four main categories: Provisioning services, which cover the supply of food, fiber, and energy resources; Regulating services, including climate moderation, pest management, and purification of air and water; Supporting services, such as soil development and nutrient recycling; and Cultural services, which add spiritual, aesthetic, and recreational benefits. Agriculture is closely interlinked with these services; it relies on them while also influencing them. However, unsustainable farming and land use practices can destabilize ecosystems, weaken their resilience, and heighten the exposure of farms to climate variability and extreme events. Assessing the value of these ecosystem contributions is therefore critical for both ecological understanding and policy design aimed at sustainable food systems. Shifting towards sustainable farming approaches is key to ensuring long-term food security alongside ecological balance. Through the adoption of agroecological principles, conservation-oriented practices, organic methods, and climate-smart strategies, farmers can reinforce ecosystem services and strengthen the adaptive capacity of agricultural landscapes. This article explores sustainable farming practices that nurture ecosystem services, underlining their importance in building resilient food systems and safeguarding environmental sustainability.



Key sustainable agricultural practices

Sustainable agricultural practices integrate ecological principles to enhance productivity while preserving environmental integrity. These practices help to increase productivity while safeguarding nature, enhancing soil fertility, conserving water, supporting biodiversity, and reducing climate impacts. The following approaches are essential for promoting sustainability in agriculture and for enhancing ecosystem services.

Crop diversification and polycultures: It represents an ecologically sound strategy that integrates multiple crop species within a single farming system to improve productivity, soil fertility, and resilience to climate variability. By moving away from monocultures,

Innovative practices of sustainable agriculture for improved ecosystem services

diversified systems enhance nutrient cycling, reduce pest and disease pressure, and prevent soil degradation, thereby strengthening ecosystem stability. Such systems also promote efficient use of natural resources like water, sunlight, and soil nutrients, contributing to higher long-term productivity and environmental balance. In addition to ecological advantages, diversification generates economic benefits by allowing farmers to shift from low-value traditional crops to more profitable options that suit local agro-climatic conditions and socio-economic needs. Cultivating cereals, pulses, oilseeds, and vegetables not only supports market demand but also improves food security, dietary diversity, and rural livelihoods. For instance, the rice–wheat cropping system in the Indo-Gangetic plains has led to environmental stress and economic inefficiencies. Replacing water-intensive crops with alternatives such as maize, pulses, oilseeds, mustard, chickpea, and mung bean offers a practical pathway toward sustainability. These crops reduce water use, enrich soil fertility, and provide higher economic returns, thereby promoting resource conservation, ecological resilience, and enhanced farmer income.

Conservation tillage and cover cropping: These are essential practices for sustainable soil management, offering both environmental and agronomic benefits. Conservation tillage reduces soil disturbance, helping retain organic matter, improve water infiltration, and minimize erosion, thereby enhancing resilience and soil structure. Cover cropping, using species like cowpea, clover or rye, provides continuous soil cover that prevents erosion, enriches fertility, suppresses weeds, and fosters beneficial microbial activity. Together, these practices improve soil's physical, chemical, and biological health while reducing reliance on synthetic fertilizers. Importantly, they contribute to climate change mitigation by sequestering carbon—cover crops alone can store up to 0.22 tonnes of carbon per acre annually. By promoting nutrient cycling, conserving water, and enhancing biodiversity, these methods deliver critical ecosystem services. As climate-smart strategies, they strengthen long-term productivity, ensure food security, and advance sustainability in agricultural systems.

Agroforestry systems: Agroforestry is a sustainable land use approach that integrates trees, shrubs, and crops within farming systems to deliver ecological and economic benefits. By improving soil structure, enhancing water regulation, and sequestering carbon, agroforestry plays a critical role in climate change mitigation and adaptation. It also enriches biodiversity by providing habitats for pollinators, birds, and other beneficial organisms, while generating additional income from timber, fruits, fodder, and medicinal plants. Research highlights its strong carbon storage potential in both tree biomass and soils. For example, poplar based systems in Punjab sequester nearly 8.9 Mg C/ha/yr, while teak and Acacia based systems in eastern and northern India also demonstrate high carbon capture. By improving soil fertility, diversifying farm outputs, and strengthening resilience, agroforestry emerges as a climate smart practice that enhances ecosystem services while supporting sustainable agriculture and rural livelihoods.

Efficient irrigation and rainwater harvesting: Sustainable agriculture in water stressed regions requires efficient water management. Advanced irrigation technologies such as drip and sprinkler systems minimize water loss, maintain ideal soil moisture, and enhance crop yields while conserving resources. Complementing these, rainwater harvesting and storage helps water availability during dry spells. Together, these strategies significantly improve water-use efficiency, reduce dependency on overexploited groundwater. Beyond water conservation, efficient irrigation enhances soil health and improves nutrient cycles. By maintaining balanced soil moisture, these practices also foster ecosystem services like nutrient retention, and carbon sequestration. Efficient irrigation and rainwater harvesting not only sustains productivity but also strengthens agroecosystem resilience.

Organic farming and biopesticides: Unlike conventional systems, organic farming avoids synthetic fertilizers and pesticides, relying instead on composting, crop rotation, green manures, and biological pest control to maintain fertility and crop protection. Biopesticides, derived from bacteria, fungi, or plant-based extracts, provide eco-friendly pest management while reducing chemical residues and safeguarding beneficial organisms. These practices improve soil microbial diversity, foster nutrient cycling, and contribute to ecosystem stability. Importantly, organic systems help mitigate climate change by lowering greenhouse gas emissions linked to fertilizer production and application. By promoting ecological resilience, improving food safety, and conserving natural resources, organic farming and biopesticides serve as vital tools for advancing sustainability in agriculture and reinforcing ecosystem services.

Precision nutrient and water management: Adopting precision nutrient and water management is vital for creating resilient and sustainable farming systems. By incorporating bio fertilizers and site-specific nutrient application, nutrient uptake can be improved and greenhouse gas emissions can be lowered. Smart tools such as SPAD meters, leaf colour charts, and Greenseeker enable optimized nitrogen use, reducing nitrogen application by 12–25% in rice-wheat systems without compromising yields, thereby reducing pollution and conserving resources. Precision water management plays an equally critical role. Practices like direct-seeded rice (DSR) eliminate puddling, conserve water, cut labour costs, and significantly reduce methane emissions compared to traditional rice systems. Similarly, intermittent wetting and drying (IWD) techniques conserve irrigation water while lowering methane release from paddy fields. Together, these strategies not only boost crop productivity but also improve nutrient cycling, protect soil and water quality, and enhance ecosystem services, ensuring long-term sustainability.

Climate smart agriculture (CSA): CSA integrates innovative practices and technologies to combat climate change, enhance productivity, and ensure sustainability. Its core objectives include improving food security, strengthening resilience to climate variability, and reducing greenhouse gas emissions. In India, two widely recognized CSA innovations are the Laser land leveller and the Happy seeder, both recommended for smallholder climate adaptation. The Happy seeder, a zero-tillage seed drill, eliminates residue burning, thereby reducing labour costs by 80%, irrigation demand by 20–25%, and herbicide use by 50%. By retaining rice residues as mulch, it enriches soil organic matter, conserves moisture, and improves seedbeds. Studies show it can increase farm profits by 20% and cut emissions by 78% compared to residue burning. The Laser land leveller further promotes sustainability by improving water efficiency through uniform distribution, collectively enhancing ecosystem services and climate resilience.

Biodiversity conservation: Pollinators such as bees, butterflies, and birds are vital for food production and maintaining ecological balance. Pollinator-friendly practices like planting wildflower strips, reducing pesticide use, and diversifying crops, help secure food supplies while conserving habitats. Preserving natural areas within farms sustains pollinators and natural pest predators, improving both crop yields and ecological resilience. Ecological corridors that connect fragmented landscapes further strengthen biodiversity and ecosystem health. However, large-scale monocultures, such as continuous rice–wheat systems, have led to soil degradation, stagnant yields, greenhouse gas emissions, and pest outbreaks. To address these challenges, Integrated Farming Systems (IFS) promote diversified approaches including agroforestry, cover cropping, and polyculture. Examples such as rice-fish-duck farming enrich soil microbial diversity through natural organic inputs like compost and manure. Integrating trees within farms also provides windbreaks, enhances biodiversity, and generates additional income. By combining productivity with ecological care, IFS supports sustainability while enhancing critical ecosystem services.

Benefits of sustainable agriculture for ecosystem services

Enhanced soil fertility and structure:

- Crop rotation, cover cropping, and reduced tillage build organic matter and improve soil health.
- Agroforestry and composting boost nutrient cycling and microbial diversity.

Improved water quality and availability:

- Conservation tillage and organic farming reduce runoff, erosion, and agrochemical pollution.
- Drip and sprinkler irrigation optimize water use and conserve groundwater.

Carbon sequestration and climate mitigation:

- Agroforestry and cover crops store carbon in biomass and soils.
- Reduced reliance on synthetic fertilizers lowers greenhouse gas emissions.

Increased biodiversity and habitat stability:

- Farmlands support pollinators, natural predators, and wildlife.
- Diverse cropping prevents pest outbreaks and strengthens ecological resilience.

Strengthened food security and livelihoods:

- Resilient farming improves yields under climate stress.
- Diversified systems provide multiple income streams and reduce risks.

Challenges and barriers to adoption

High financial burden:

- Initial investments in technologies like precision tools, CSA equipment, and water-efficient irrigation are costly.
- Limited access to credit and uncertain short-term returns discourage smallholder adoption.

Knowledge and skill constraints:

- Farmers often lack awareness, technical training, and extension support to effectively adopt sustainable methods.
- Complex agroecological principles and slow knowledge transfer.

Cultural and behavioural resistance:

- Deep-rooted traditional practices, cultural beliefs, and scepticism about new techniques create reluctance to change.

Market and incentive limitations:

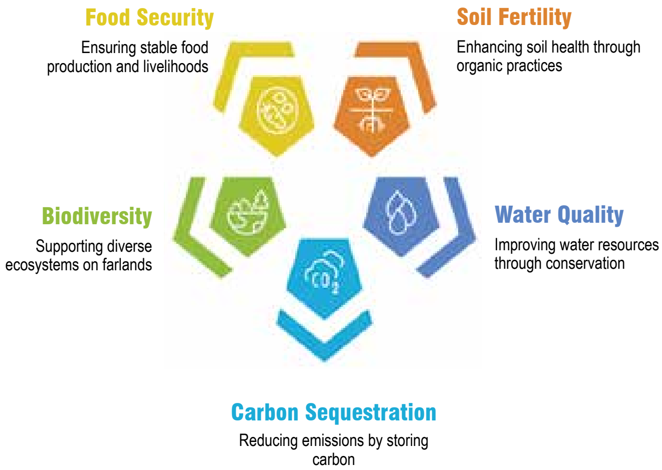
- Current market structures favour conventional farming.
- Lack of premium markets and incentives for sustainably produced goods reduces motivation.

Uncertainty in outcomes:

- Concerns over yield stability, market viability, and profitability discourage long-term commitment to sustainable farming.

Policy and technical support

- ***Institutionalize payment for ecosystem services (PES):*** Develop a national framework to reward farmers for ecosystem services like carbon sequestration, biodiversity conservation, and water-use efficiency.
- ***Green/Carbon credit markets:*** Strengthen the Green Credit Programme (GCP) and Voluntary Carbon Market (VCM) to generate tradable credits from climate-smart practices.
- ***Government schemes with PES:*** Redesign schemes like Rashtriya Krishi Vikas Yojana (RKVY) to link incentives with measurable ecosystem services (soil carbon, groundwater recharge, tree cover, and emission reduction).
- ***Research and innovation:*** Increase investments in precision farming, biofertilizers, water-efficient technologies, and resilient crop varieties aligned with PES objectives.
- ***Partnerships and community action:*** Promote public-private partnerships, farmer cooperatives, and knowledge-sharing networks for wider adoption of PES-based practices.
- ***Blending knowledge systems:*** Integrate traditional farming wisdom with modern technologies to enhance sustainability, resilience, and resource efficiency.



Sustainable agriculture's ecosystem benefits

SUMMARY

Sustainable agriculture approaches/practices such as crop diversification and polycultures, conservation tillage and cover cropping, organic farming, use of biopesticides, efficient irrigation practices, rainwater harvesting and efficient utilization, climate smart agriculture practices, precision nutrient and water management and biodiversity conservation are essential for promoting sustainability in agriculture and for enhancing ecosystem services. To overcome the limitations in adopting these practices, certain policy and technical interventions are needed.

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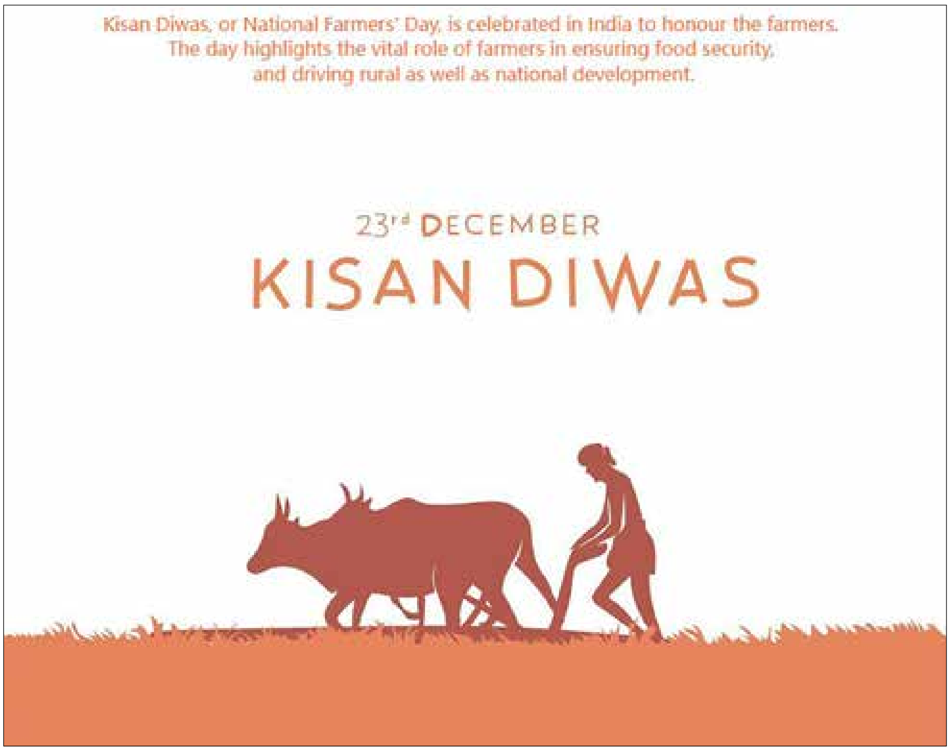

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Adoption of modified agronomic

approaches for sustaining crop productivity

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Agronomy feeds the world as it is the applied science for management of natural resources to improve the production of crops for ensuring a sustained supply for the growing global population. Agronomists focus on efficient crop and soil management, nutrient, weed and water management as well as climate to develop suitable practices to boost yields and enhance food quality while protecting the natural resource base. An analysis shows that more than half of the total increase in foodgrain production in India during the Green revolution period (mid-1960s to mid-1970s) was attributed to efficient nutrient and water management. However, the productivity levels started stagnating or even declining during the 1990s owing to resource degradation and several other challenges including the climate change in the present times. There is now an urgent need to revise our strategies and adopt modified agronomic approaches for more efficient management of crop, soil, nutrient, weed, water and energy for sustaining crop productivity.

Keywords: Conservation agriculture, Crop residues, Integrated management, Sustainability, Zero tillage

INDIA faced acute food shortages before and also after independence, leading to widespread hunger, malnutrition and dependence on imports. During the mid-1960s, there was a quantum jump in foodgrain production, often termed as the green revolution. This was possible due to the introduction of high-yielding varieties of major crops like rice and wheat, duly supported by increased use of chemical fertilizers and expansion of irrigation facilities. It is often said that if the HYV seeds were the vehicle, fertilizers proved to be the fuel, which led to the Green revolution. By early 1980s, India achieved complete self-sufficiency in foodgrain production and also started building the capacity to have sufficient buffer stock and some exports as well.

Degradation of natural resources and deterioration of soil health have emerged as a major issue in the past two decades due to the adoption of Green revolution technologies. These practices have led to emerging challenges such as declining factor productivity, deterioration of soil health, surface and groundwater pollution, thus increasing cost of production and lower profitability. It is said that our soils have become addicted to chemical fertilizers and further getting impoverished due to imbalanced use of fertilizers, discontinuation of traditional practices like mulching, intercropping and inclusion of legumes in cropping systems. Organic manures like FYM were traditionally used for meeting the nutritional requirement of crops for a subsistence level of crop production, but their use decreased substantially for various reasons.

Competing demands for water and excessive exploitation of groundwater resources have led to lowering of ground water table, and pollution of water bodies due to various human interventions. Climate change has emerged as the biggest threat in the present times owing to the emission of greenhouse gases, which is partly due to the burning of fossil fuels for meeting the energy demands of higher crop production. Faulty cultivation practices such as burning of crop residues, puddling for rice cultivation, excessive dependence on chemical fertilizers and flood irrigation are responsible for global warming. There has been reports of stagnating trend in crop productivity since the 1990s, raising serious concerns about sustainability. There is growing realization that a change is needed in the present system of crop production so that the natural resources are not harmed, and the production levels are not only sustained but also improved for meeting the demands of the posterity.

Agronomic approaches for sustaining crop productivity

In the later part of the previous century, improved agronomic technologies were developed for increasing agricultural production. This in a way led to a sort of another revolution as it changed the way the crop production was carried out in many regions of the world. Firstly, the new generation farm machinery was developed and made available at affordable cost, which replaced the dependence on manual or animal-drawn power for tilling the land and various other farm operations. Secondly, innovations in chemical-based herbicides led to efficient weed control at nominal cost, and virtually replaced the arduous task of manual weeding in most crops. Further, other triggering factors for shift towards new innovative approaches are labour scarcity, deteriorating soil health, declining factor productivity, rising cost and low income. Thus, the modified agronomic approaches are needed in overcoming the problems being experienced in conventional farming systems.

Tillage and crop establishment: The first essential requirement of successful crop production is to ensure good initial crop stand and vigour. If this requirement is not met, all other operations later often fail to compensate for the loss in yield. Broadcasting, still prevalent in most areas, or sowing with manually- or animal-drawn implements often fails to ensure good crop stand. Besides ensuring good quality seeds, sowing must essentially be done by the seed drills, which can place the seed as well as basally-applied fertilizer close to each other.

Most tractor-drawn drills are so designed as to place the fertilizer typically 2–3 cm below the seed. Zero-till seed-cum-fertilizer drills of normal type (knife-type) for sowing in residue-free or in anchored residue conditions, and Happy Seeder in anchored or loose residue conditions are now available. Conservation agriculture involving zero/ minimum tillage, residue mulching and crop rotations has been found to result in equally good or even better crop stand and higher productivity. This technology has been adopted globally on a large scale, and must also be followed in all possible domains in India for efficient management of natural resources and sustaining crop productivity.

Crop residue recycling: It is often argued that crop residues are not available for recycling in crop production as these are meant for animal fodder in most regions of the country. But the reality is that with combine harvesting of most crops with now easily available custom hiring services, the crop residues are left in the field. The easiest way for the farmers to dispose of these residues for preparing the field for the next crop is to burn *in situ*. This has emerged as a national problem as it not only pollutes the environment but also destroys the beneficial soil microflora and fauna, and deprives the soil of plant nutrients. It is now being advocated that 'grains for human beings and crop residues for the soil', and first claim on the crop residues is of the soil so as to replenish its fertility status.

Residue retention on soil surface, and not necessarily its incorporation into the soil, which is energy-intensive process and causing immobilization of native nutrients, brings about enormous changes in the rhizosphere beneficial for crop growth. It promotes biological tillage through the activity of earthworms and soil microorganisms, and the soil in fact becomes more porous and friable over a period of time. Residue retention also modifies the micro-climate, and helps in soil moisture conservation, weed control, temperature moderation in the soil as well as within the crop canopy, and enhances the fertility of the soil. The Government of India has formulated a policy to dissuade the farmers from burning the crop residues and providing various incentives for their alternative and beneficial utilization.

Integrated weed management: Weeds are considered even a greater constraint in crop production than meeting the nutritional and water requirement of crops. It was perceived since the ancient times that the soil should be well pulverised before sowing, primarily to control weeds. However, with intensive tillage operations, the soils became more prone to erosion hazards due to wind and water. This emerged as the major issue in the advanced countries during the 1970s which led to innovation of ploughless cultivation systems. Evidently, such systems required alternative and more efficient strategies for weed control.

Conservation agriculture involving zero tillage requires placement of seed and fertilizer close to each other below the soil, the inter-row spaces remain virtually undisturbed, rather these are covered with the mulch of crop residues. Weed seeds lying in the upper soil layer (0–5 cm) emerge in the first flush after sowing, which are easily killed with a pre-emergence or early post-emergence herbicide application. There is relatively lower emergence of weeds in the subsequent flushes after a month or so, by which time the crop has also developed adequate canopy to suppress their growth. A suitable post-emergence herbicide is also applied as per availability and requirement of the situation. Season-long weed control is needed, and the old concept of managing weeds only during the period of critical crop-weed competition is not relevant in the long-term.

Integrated weed management is the solution for holistic weed control in crop production systems. In view of the concerns being expressed for using agro-chemicals including herbicides in a rather indiscriminatory manner and the associated residues and health hazards, there is certainly a need to reduce the chemical load in crop production systems. However, it is also a reality that herbicides have now become indispensable for large scale weed control in view of their greater efficiency and much lower cost compared with manual or mechanical weeding. It is essential that we must integrate all the available methods of weed control including the non-chemical measures involving minimum tillage, cover cropping and crop rotations. A greater focus is also required on the preventive methods of weed management so that the control measures are needed minimum in crop production system.

Integrated nutrient management: Efficient nutrient management is an essential requirement for successful crop production. Conventional practice for fertilizer application advocates 4R stewardship– Right kind, right dose, right time, and right method, but quite

Wheat sowing in rice residues with Happy seeder

often, there is greater emphasis on dose and time of application/splits. Further, the fertilizer use is highly imbalanced (N : P : K ratio of 12 : 5 : 1 instead of the generalized norm of 4 : 2 : 1). Surface broadcasting of fertilizers and blanket application without any regard to the inherent soil fertility is the most inefficient practice. The new approaches to fertilizer application involve soil-test based balanced fertilization including use of secondary/micro-nutrients, greater emphasis on method of application–placement close to the seed/plant roots even while top dressing of urea fertilizer before irrigation.

Integrated nutrient management is the key to sustain soil health and crop productivity. It is not possible to ensure continued nutrient supply with chemical fertilizers alone and long-term soil fertility. All the available sources of plant nutrients including the available organic manures, crop residues, green manures, tree loppings, weed biomass, and biofertilizers must be integrated with chemical fertilizers. In fact, an ideal approach is to combine 50% each of chemical fertilizers and non-chemical sources for meeting the nutritional requirement of crops.

Precision nutrient management practices involving various sensors and modelling approaches have been worked out and shown to be promising. However, despite decades of research, these have hardly found any acceptance and adoption on the farmers' fields due to lack of awareness, inconsistent response and poor delivery systems. Liquid fertilizers have been shown to have better efficiency in advanced countries but these are yet to be tested on a large scale under Indian conditions.

Irrigation management: Conventional practice of irrigation involves flooding which results in lot of wastage of water, increases weed infestation and lowers nutrient use efficiency. This practice can no longer be afforded in view of the competing demands for water, and we must go in for more efficient water-saving technologies. Retention of crop residues on the soil surface, as under conservation agriculture, prevents evaporation loss of soil moisture, and keeps the soil in relatively wetter condition for a longer period of time. Crop residues remaining as mulch on the surface gradually decompose through the action of water applied through irrigation, N fertilizer as top dressing, and build-up of microbial populations in the soil.

Non-conventional approach of scheduling irrigation involves adoption of micro-irrigation systems–sprinkler and drip including sub-surface drip irrigation. These systems improve efficiency of water and nutrient use and weed control, leading to saving of water, fertilizer and herbicide. The luxury of flood irrigation can no longer be afforded, rather it should be banned, and micro-irrigation systems should be promoted in all possible domains. Conjunctive use of problem waters along with good quality waters is necessary for meeting the water requirement of plants. Collecting, conserving, and utilizing 'every drop of water for more crop' should be the motto for efficient water management.

Integrated farming systems: 'Business as usual' will not work in the context of crop production as well. In many areas, there has been a significant shift in the cropping system over the years due to non-profitable farming, changing weather patterns, irrigation water availability, easiness of weed control, mechanization, labour scarcity and market demand. In the Bundelkhand region, the traditional crops in the rainy season like mungbean, urdbean, sesame and millets have virtually disappeared from many areas, and replaced by groundnut, maize and rice. Similarly in Himachal Pradesh, the farmers are even abandoning cultivation of traditional maize, rice and wheat crops due to the growing menace of domestic and wild animals, non-availability of manpower and other local constraints, and going in for high-value horticultural crops. There is an urgent need to diversify the cropping system as per the changing needs in order to remain relevant and make farming sustainable on a long-term basis.

Agriculture does not involve crop production alone but also a host of other activities like animal husbandry, fisheries, bee keeping, mushroom, horticulture, agroforestry, etc. These need to be integrated well based on location-specific requirements and availability of resources to provide security and ensure sustainability. Circular economy by utilizing byproducts of one enterprise into another, and the concept of 'waste-to-wealth' is very relevant for optimizing returns, conserving natural resources, mitigating climate change and associated risks for ensuring water and food security.

Small farm mechanization: Conventional production systems have relied on manual labour or bullock energy for most field operations, which is no longer relevant in the present context due to non-availability of labour and resulting high cost. Near complete mechanization is the need of the hour for making crop production profitable and competitive in the local and global market. New machines such as Happy seeder which sows in no-till residue-mulch conditions, super seeder which mixes the residue in the top soil layer before placing seed and fertilizer, and roto-double disc drill which can work with less energy requirement and in heavy residue load have been developed and perfected for sowing. Similarly, innovative farm machines are available for weeding, interculturing, irrigation scheduling, fertilizer application, spraying, harvesting and post-harvest operations. Drones and artificial intelligence-based robots are likely to become a reality in the coming years, which will change the complexion of crop production scenario in the country.

It is no longer possible to do crop production with the traditional way of farming using the manpower resources even by the small holder farmers. Previously, it was thought that only the big farms need mechanization, but in the present times, small and marginal farmers equally need to adopt labour-saving technologies. While big machines may not be applicable in all situations, the small farm machinery is needed suited to local requirements, even in the hilly and inaccessible terrains. This is now possible with the establishment of custom-hiring centres in most states and provision of subsidy for procurement of farm implements. Government of India has introduced various policy reforms to provide easy access to quality farm machinery, which can do the required operations timely and more efficiently at much lower cost.

SUMMARY

Agronomy has played a significant role in developing improved production technologies through efficient utilization of natural resources and external inputs since the green revolution. The various agronomic interventions enabled the HYVs to exhibit their near full production potential and eliminated the acute foot shortages in the country. However, now with the emergence of post-Green Revolution and other 21st century challenges including the climate change, there is required to be a renewed thinking to suitably modify the agronomic interventions for sustained productivity. We need to reorient our strategies aimed at more efficient utilization of resources, reducing the cost of production and enhancing profitability, ensuring climate resilience and quality produce for domestic as well as export purposes.

There is a need for thorough testing and verification of the research findings in the real farming situations on a large scale before translating these into technologies and making recommendations to the farmers. Tall claims made by the agronomists based on short-term small-plot on-station experimentation often fail to produce the desired results on the farmers' fields. Therefore, farmer-centric research in close association with all the stakeholders must be undertaken for technology generation. Further, necessary back-up in the form of suitable policies for farm machinery procurement, subsidised and assured input supply, and market access is required to be provided to enable farmers adopt modified agronomic approaches.

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From weed to feed: Role of Lantana biochar in chickpea productivity

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Indian agriculture has made significant progress in achieving self-sufficiency in food grain production and has attained a growth rate sufficient to meet the demands of the growing population. Although the production of pulses has increased in the past decade, it has not kept pace with the growing population. Since pulses are a major source of protein in the Indian diet, as well as resource-conserving and environmentally friendly, enhancing their production can help address challenges such as nutritional security and reduction of dependence on imports.

Keywords: Environmentally friendly, Pulses, Resource-conserving

LANTANA *camara*, a widespread invasive weed, can be sustainably repurposed as biochar, a potent soil amendment. Lantana, ranked among the top 10 invasive species globally, poses significant threats to biodiversity, public health, and livestock. Recent field experiments reveal that Lantana biochar significantly improves chickpea growth, yield, and soil health, transforming a problematic weed into a valuable resource for sustainable agriculture. Its biomass, however, presents an opportunity: When processed into biochar through slow pyrolysis, it yields a carbon-rich soil amendment with high porosity and nutrient retention characteristics. Chickpea (*Cicer arietinum* L.), a key pulse crop, stands to benefit from improved soil quality and nutrient availability facilitated by biochar amendments.

Biochar production and application protocols

Lantana biochar was produced through slow pyrolysis using a biochar production system (Pratap Kiln) developed at CTAE, Udaipur. Stalks of *Lantana camara* were fed into the pyrolysis reactor under oxygen-limited conditions, where the temperature reached up to 450°C for a duration of four minutes. The process involved three stages: In the first stage, the moisture content of the biomass was reduced to below 10% at around 180°C; in the second stage, biochar formation began with the decomposition of hemicellulose and cellulose within the temperature range of 180–360°C; and in the final stage, lignin decomposition occurred at approximately 450°C. In field experiments, biochar doses of 1.5, 2.5, and 3.5 t/ha were compared, with split application (50% at sowing and 50% at branching) found optimal for chickpea productivity.

Description of chemical composition of *Lantana camera*

Lantana camara contains a wide range of chemical constituents. Its essential oils are primarily composed of monoterpenes and sesquiterpenes such as sabinene, eucalyptol, caryophyllene, and humulene, along with triterpenoids, steroids, alkaloids, and flavonoids.

Table 1. Mineral composition of *Lantana camara*

Minerals	Composition (ppm)
Phosphorus (P)	0.07 ± 0.01
Cacium (Ca)	0.53 ± 0.01
Manganese (Mn)	0.98 ± 0.03
Sulphur (S)	0.74 ±0.02
Potassium (K)	1.06 ± 0.03
Iron (Fe)	0.83 ± 0.02
Magnesium (Mg)	0.43 ± 0.03
Copper (C)	0.54 ± 0.01

Agronomic effects on chickpea

Growth and yield enhancement:

Doses of lantana biochar: In the present investigation, the application of 3.5 t/ha lantana biochar resulted in a significantly higher seed yield of 1436 kg/ha, representing a 34.51% increase over the control (1067 kg/ha). Similarly, haulm yield was significantly enhanced with 3.5 t/ha lantana biochar, recording 3523 kg/ha, which was 50.02% higher than the control (2348 kg/ha). The maximum biological yield of 4959 kg/ha was also achieved with 3.5 t/ha lantana biochar, whereas the minimum biological yield (3416 kg/ha) was observed under the control treatment.

Stages of application: Application of Lantana biochar at different crop growth stages resulted in a significant improvement in seed yield (1386 kg/ha), haulm yield (3334 kg/ha), and biological yield (4720 kg/ha) compared to its application only at the time of sowing. This enhancement may be attributed to greater nutrient availability throughout the crop growth period, as biochar was applied in split doses. The split application extended the duration of nutrient supply and improved the soil's water-holding capacity due to the porous structure of Lantana biochar. These combined effects enhanced crop growth and led to an increased number of pods per plant, ultimately resulting in higher seed, haulm, and total biological yield of chickpea.

Table 2. Effect of application of lantana biochar on chickpea

Treatments	Number of effective Nodules/plant	Number of branches/ plant	Number of pods/plant
Doses of lantana biochar (t/ha)			
Control	16.23	8.58	65.99
1.5	17.99	9.44	71.72
2.5	19.65	10.20	77.66
3.5	20.40	10.60	82.60
S.Em±	0.483	0.184	1.899
C.D. at 5%	1.395	0.532	5.484
Stages of application			
At sowing	16.07	8.71	66.55
At branching	19.28	9.92	75.64
At pod formation	18.22	9.61	74.44
50% at sowing + 50% at branching	20.69	10.57	81.35
S.Em±	0.483	0.184	1.899
C.D. at 5%	1.395	0.532	5.484

Table 3. Effect of application of lantana biochar on yields of chickpea

Treatments	Seed yield (kg/ha)	Haulm yield (kg/ha)	Biological yield (kg/ha)
Doses of lantana biochar (t/ha)			
Control	1067	2348	3416
1.5	1216	2897	4113
2.5	1365	3382	4717
3.5	1436	3523	4959
S.Em±	25.81	72.03	74.25
C.D. at 5%	74.56	208.05	214.46
Stages of application			
At sowing	1161	2762	3922
At branching	1279	3057	4337
At pod formation	1258	2997	4255
50% at sowing + 50% at branching	1386	3334	4720
S.Em±	25.81	72.03	74.25
C.D. at 5%	74.56	208.05	214.46

Soil health

Different doses of Lantana biochar have been shown to significantly increase the availability of nitrogen and phosphorus in soil. The highest available nitrogen was recorded with the application of 3.5 t/ha Lantana biochar compared to the control. Specifically, available nitrogen and phosphorus increased by 5.41% and 9.35%, respectively, over the control; these improvements were statistically similar to results seen with the application of 2.5 t/ha Lantana biochar. Soil dehydrogenase and microbial biomass also improved, indicating boosted soil biological activity. Biochar minimizes the nitrogen losses by reducing the leaching losses, increasing the bioavailability, higher nitrogen fixation. Thus from the above findings, it is clear that biochar application improves the chemical and biological properties of soil in a long term.

Table 4. Effect of application of lantana biochar on soil microbial biomass in soil after crop harvest

Treatments	Bacteria (106)	Fungi (104)	Bacteria (105)
Doses of lantana biochar (t/ha)			
Control	63.15	22.95	34.45
1.5	68.59	24.13	37.82
2.5	74.41	26.36	41.11
3.5	75.61	26.69	41.31
S.Em±	0.757	0.268	0.500
C.D. at 5%	2.187	0.774	1.443
Stages of application			
At sowing	63.09	22.74	34.62
At branching	71.65	25.48	39.65
At pod formation	71.08	24.82	39.26
50% at sowing + 50% at branching	75.94	27.07	41.17
S.Em±	0757	0.268	0.500
C.D. at 5%	2.187	0.774	1.443

Economic analysis

The highest net returns were obtained for 3.5 t/ha Lantana biochar (₹ 53,672/ha) and for split application (₹ 59,028/ha), proving the economic advantage of biochar adoption in chickpea cultivation.

Environmental benefits

Utilizing *Lantana camara* for biochar production helps control its invasive spread, reduces ecological damage, and recycles a problematic weed into a valuable resource for sustainable agriculture and soil management. Utilizing *Lantana camara* for biochar production provides multiple environmental benefits:

- It helps control the invasive spread of Lantana, preserving native biodiversity and preventing ecological damage caused by dense thickets and allelopathic effects.
- Converting Lantana into biochar mitigates health risks associated with the plant (such as skin irritation and respiratory issues) by stabilizing toxic compounds through pyrolysis.
- Lantana biochar effectively adsorbs pharmaceutical pollutants like acetaminophen from wastewater, addressing water contamination issues and aligning with sustainable development goals for clean water and health.

View of field experiment

Effect of lantana biochar on number of effective nodules at 45 DAS

- The biochar acts as a carbon sink, contributing to carbon sequestration, which helps mitigate climate change.
- This approach provides a renewable, eco-friendly solution that recycles a problematic invasive species into a valuable product for soil amendment, environmental remediation, and water treatment.

Mechanisms behind productivity gains

Soil physical and chemical improvements: Lantana biochar amendments improve soil water retention, cation exchange capacity, and porosity due to the biochar's particulate, porous nature. It also increased nutrient availability and retention in soil, particularly nitrogen and phosphorus, enhance root and shoot growth in chickpeas.

Microbial and biological impacts: Biochar supports beneficial soil microflora (bacteria, fungi, and actinomycetes), vital for nutrient cycling and plant health. These biological changes translate into greater pod development and seed weight, directly impacting yield.

Application strategies and recommendations: The evidence strongly supports using Lantana biochar at 3.5 t/ha, ideally split between sowing and branching stages for chickpea. Split dosing increases the period of nutrient availability, improving chickpea yield parameters versus single, one-time application.

Broader implications and future directions

Repurposing *Lantana camara* as biochar provides a dual benefit: weed management and soil fertility enhancement for sustainable intensification of chickpea agriculture. This approach aligns with broader goals of organic and resilient farming systems, offering pathways for reducing dependence on chemical fertilizers and improving smallholder livelihoods.

SUMMARY

Application of 3.5 t/ha lantana biochar resulted in the highest seed yield (1436 kg/ha, a 34.5% increase over control), haulm yield (3523 kg/ha), and total biological yield (4959 kg/ha). Split application (50% at sowing + 50% at branching) significantly increased yield compared to single dosing, owing to sustained nutrient availability. Lantana biochar transforms a widespread weed into a feeder for sustainable agriculture. Its integration into chickpea farming systems boosts plant productivity, soil fertility, and farm profitability, providing an innovative, eco-friendly solution for weed utilization and crop enhancement.

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Digital agriculture and data-driven farming

solutions for sustainable development

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Indian agriculture is undergoing a digital shift, propelled by technologies such as drones, farm robots, and smart soil sensors, particularly in regions dominated by small and marginal farmers. This transition addresses pressing challenges including labour scarcity, water limitations and climate variability. Since the last decade, rapid integration of robotics, remote sensing, GIS, artificial intelligence, machine learning and IoT has enabled precise crop monitoring, targeted input delivery, and efficient resource management. These tools operate by collecting and analyzing real-time field data, translating it into actionable decisions for irrigation, fertilization and pest control. The outcome is a resilient, resource-optimized farming model capable of sustaining productivity while reducing environmental impacts across diverse agro-climatic zones in India.The convergence of digital tools is not only modernizing farm operations but also empowering smallholders with decision support systems and mobile-based advisories. This evolution underscores the potential of digital agriculture to transform Indian farming into a climate-resilient and sustainable enterprise.

Keywords: Artificial intelligence, CropX sensors, Digital agriculture, Drones, Precision farming

THE digital revolution is expected to transform traditional farming into a smarter and efficient enterprise. The integration of innovative tools such as agricultural drones, robots and advanced soil sensor technologies is reshaping monitoring mechanism of crop health. These advancements are being tailored to meet the needs of small and marginal farmers too. Drones now facilitate accurate spraying, seeding and crop monitoring, reducing chemical use and labour costs. Farm robots reduce drudgery and improve operational efficiency, while soil sensors enable data-driven decisions for precise input management. Furthermore, the blend of Remote Sensing (RS), Geographic Information Systems (GIS), Artificial Intelligence/Machine Learning (AI/ML) and the Internet of Things (IoT) is driving dynamic and responsive farming. Together, they drive climate smart farming by overcoming extreme events, resource scarcity paving the way for sustainable agriculture.

Digital agriculture solutions

Drones in agriculture-Operational applications:

Precision spraying: Ensures accurate chemical application with minimal wastage and investment, enhanced safety, and lower environmental impact.

Drone-mounted seed and fertilizer spreader in rice

Granular application (Dry spreading): Provides precise, timely material placement without crop damage or soil compaction, lowering per-acre costs.

Seed and fertilizer spreader in rice: Improves planting efficiency, reduces labour, and enables operation in difficult terrains while offering real-time seeding data.

Drone aided broadcasting with 10 kg capacity seed and fertilizer spreader achieved 85–90% distribution uniformity, 65–70% less labour cost with 80% time savings leading to reduction in seeding cost to ₹ 1000–1125/ha from ₹ 1750–2000/ha in rice dry direct seeding (DDSR) in Andhra Pradesh.

CropX sensor- Data-driven soil intelligence: The CropX soil sensor system uses IoT-based sensors to continuously measure soil moisture, temperature, and electrical conductivity at multiple depths, enabling precise irrigation and nutrient management. It combines hardware, telemetry, soil sensors, real-time environmental data, crop models, and farm machinery inputs to provide holistic assessments. Advanced analytics generate predictive insights and recommendations, accessible through a customizable dashboard that supports multi-farm management, tailored visualizations, and inter-user communication. It offers a suite of modules for smart farm management, including field data integration, irrigation scheduling, nutrition monitoring and disease forecasting. It also supports connectivity across farm sensors and machinery, and standardized tracking and reporting. The sensors acquire data on soil moisture, temperature and electrical conductivity, enabling the system to generate recommendations prior to the manifestation of plant stress symptoms. The CropX system in Andhra Pradesh has achieved 70% increase in sugarcane yield, 90% reduction in supplemental feed requirements for pastures, 15% decrease in fertilizer consumption and 68% reduction in water usage.

FarmRobo R: It is the India's first multi-purpose electric agricultural robot designed for small to medium Indian farms, capable of precision weeding, spraying and produce transport. Its modular quick coupler supports attachments like weeder blades, rotary tillers and a 10-foot boom sprayer. It include AI + RTK-guided navigation with obstacle avoidance, battery power for 6–8 h (covering 1.25–1.75 ha/day), OTA software updates and intuitive controls suitable for women operators. It helped in reducing weeding time to 2–3 h from 2–3 days, spraying reduced to minutes from hours and chemical use by 30%, overall costs and environmental impacts.

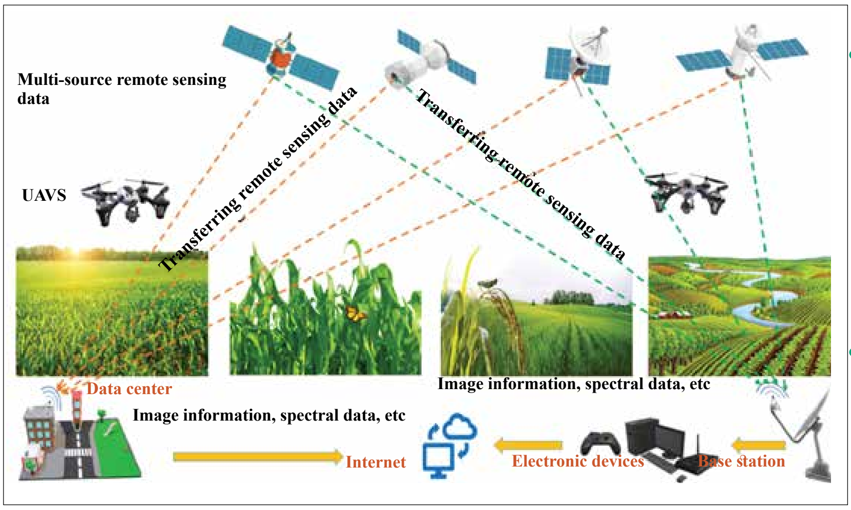
Remote sensing in agriculture: RS and GIS are being used widely in agriculture for crop identification, area and yield estimation, soil moisture monitoring, water management, pest/disease forewarning and agro-advisories. It offers advantages such as synoptic views, rapid surveys, repetitive coverage, cost-effectiveness, high accuracy and multispectral data use and enables large-scale, dynamic monitoring of crops, supporting productivity forecasting at district and regional levels.

Table 1. Application of remote sensing in agriculture

Application	Description
Crop monitoring and health assessment	Uses vegetation indices like NDVI NDWI etc. to track plant vigor, stress and growth over time. It also helps in detecting biotic stress Pest and disease) and abiotic stress (drought, nutrients, etc.)
Crop type mapping	Identify and classify different crops based on their spectral signatures during various growth stages using time-series satellite data
Yield estimation	Predicts crop yield based on the real time satellite data combined with weather and soil parameters
Soil mapping	Helps identify soil texture, salinity and moisture variability, enabling targeted soil management
Precision agriculture	Supports variable rate applications of water, fertilizer, and pesticides by mapping field variability
Non arable land identification	Detects uncultivated or underutilized lands between cropping seasons using time-series data
Change detection studies	Maps agricultural areas, forests water bodies and built-up regions to monitor land use changes.
Irrigation planning	Assists in monitoring irrigation coverage and evaluating the effectiveness of irrigation systems over time
Agroforestry area estimation	Facilitates monitoring of agroforestry areas and estimation of biomass to assess carbon sequestration
Smart farming	NaviCs high accuracy (<2m) helps in field mapping, precision input application, infrastructure planning, time synchronization, and supply chain monitoring

Table 2. Indian satellites and their applications

Satellite	Purpose/Applications	Sensors/ Features
IRS-1A/1B (1988/1991)	First generation Earth observation; used for land and vegetation studies	LISS-I, LISS-II
IRS-1C/1D (1995/1997)	High-resolution imaging for agriculture, forestry, water bodies	LISS-III, PAN, WiFS
Resourcesat-1 (2003)	Agricultural monitoring, land use, forest, soil mapping	LISS-III, AWiFS
Resourcesat-2 and 2A (2011 and 2016)	Advanced resource monitoring (cropping patterns, soil, forest)	LISS-IV, LISS-III, AWiFS
Cartosat Series (1 to 3)	High-resolution cartographic mapping; useful for watershed, soil, urban planning	PAN, high-res stereo imaging
RISAT Series (Radar Imaging)	All-weather, day-night imaging for disaster management, crop monitoring, soil moisture	Synthetic Aperture Radar (SAR)
Oceansat Series	Ocean parameters, weather forecasting, monsoon prediction, fisheries, monitoring sowing progress and crop area estimation	OceanColour Monitor (OCM), Scatterometer
INSAT Series (Meteorological)	Weather monitoring, rainfall estimation, agro-meteorology	CCD cameras, sounders, radiometers
HySIS (Hyperspectral Imaging Satellite) (2018)	Mineral mapping, vegetation health, soil properties mapping	Hyperspectral sensor (400+ bands)



Process of remote sensing

How AI and ML tools can assist in RS?

AI and ML tools can significantly enhance RS by automating data analysis, improving accuracy and enabling faster, more insightful decision-making.

Handling large and complex data: RS generates huge datasets (multispectral, hyperspectral, SAR). AI can process and analyze this high-dimensional data efficiently, finding patterns humans might miss. For e.g. ISRO's Bhuvan Portal prepares the National-scale land cover classification using multi-source satellite imagery. AI/ML assist in processing petabytes of imagery to produce high-accuracy thematic maps.

Automated image analysis:

- **Object detection and classification:** ML models can detect land cover, crops, water bodies, and infrastructure from satellite images. Using multier solution segmentation in eCognition, agroforestry in Khammam and Warangal (Telangana) was mapped with 81.5% and 86% accuracy, respectively.
- **Change detection:** AI detects time-based changes like crop growth or urban sprawl more accurately. NRSC uses it for Smart Cities, and Delhi authorities use ML and RS to monitor illegal buildings and urban trends.

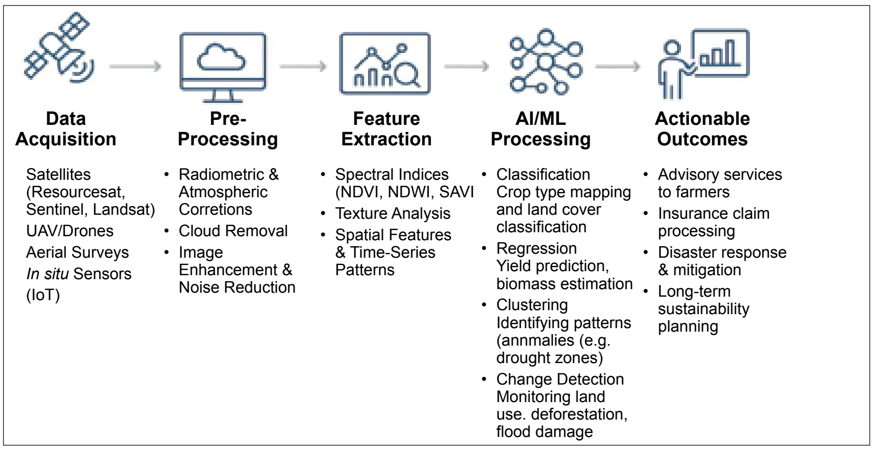
Predictive modeling:

- **Yield prediction:** AI models predict crop yieldsfromfield to national scales. MNCFC applies AI/ML with Sentinel-1, Sentinel-2, and Resourcesat data under FASAL to estimate acreage and yield at regional level, while Pradhan Mantri Fasal Bima Yojana employs AI-powered RS models for crop loss assessment for insurance claims.
- **Disaster impact forecasting:** ML predicts flood, drought, or pest impacts. The Central Water Commission and ISRO use AI-enhanced RS data for real-time flood mapping and forecasting in Assam and Bihar.

Enhancing accuracy: AI-based filtering removes atmospheric effects, sensor noise, or cloud interference. ISRO's MOSDAC (Meteorological and Oceanographic Satellite Data Archival Centre) uses AI algorithms to remove cloud contamination and atmospheric distortions from INSAT and Oceansat imagery for improved weather and ocean parameter monitoring. IIRS Dehaze and Denoise Project applies deep learning-based dehazing to high-resolution Cartosat and Resourcesat images for clearer land and vegetation analysis. ML combines data from multiple sources (optical, radar, LiDAR) to produce more reliable results. National Agricultural Drought Assessment and Monitoring System (NADAMS) combines optical (Resourcesat, Sentinel-2) and microwave (RISAT, Sentinel-1) RS data via ML models for accurate drought monitoring. Chandraprabha River Basin Study uses AI-driven fusion of LiDAR elevation data, SAR, and optical imagery for floodplain mapping and water resource planning.

Real-time monitoring: Integration with IoT sensors allows AI to process RS data in near real-time for precision agriculture, forest fire alerts, or water resource monitoring. NRSC's National Hydrology Project uses RS + AI for real-time reservoir monitoring and groundwater potential mapping.Water Resources Information System (WRIS) uses RS and ML for reservoir storage forecasting and irrigation planning. Jal Shakti Ministry Projects employs AI-based RS analysis for detecting groundwater stress zones and optimizing irrigation schedules. Forest Survey of India uses ML models on RS data for forest fire detection and burned-area mapping.

Customized decision support: AI-powered decision systems can suggest best farming practices, irrigation schedules, or resource allocation based on RS-derived insights as used by Digital Agriculture Mission in India. Indian Meteorological Department (IMD) uses RS data and



Atomization flow chart showing the frame work for RS data collection, processing, feature extraction and output generation

ML algorithms for monsoon rainfall prediction and drought early warning making predictions more robust over time. Central Water Commission Flood Forecasting combines RS imagery with ML models to predict flood extent and support disaster response.

Climate and environmental monitoring: In Andhra Pradesh and Karnataka, NICRA integrates MODIS and Sentinel-2 imagery with AI-based vegetation indices (NDVI, VCI) and ML models (Random Forest, SVM) to classify drought intensity and generate early warning maps using multi-year climate data. In Bihar, long-term RS data with climate projection models are applied to predict rice and wheat yield changes for adaptive crop planning. Similarly, ICAR-NBSSLUP uses ML regression on hyperspectral imagery to map soil organic carbon, nitrogen, and texture in Maharashtra and Punjab, while ICAR-IARI combines hyperspectral data with deep learning to detect nutrient deficiencies in wheat and paddy, delivering fertilizer advisories through mobile apps.

Integration of digital technologies: The integration of RS, GIS, AI/ML and the IoT is transforming agriculture into a data-driven, precision-based industry. The following steps gives us an insight of the procedure followed.

- **Data acquisition:** RS captures satellite/drone imagery, IoT collects field-level sensor data.
- **Data processing and GIS mapping:** GIS integrates and geo-references spatial data.
- **AI/ML analysis:** Models analyze multi-source datasets for insights.
- **Decision support:** Generates precise, timely advisories for irrigation, fertilizer application, pest control, and harvesting.

Such integration offer smart farming solutions and help enhance crop productivity, reduces costs and negative environmental impact while supporting data-driven decisions for all stakeholders.

SUMMARY

Recent advances are equipping Indian farms with highly specialized digital capabilities. Aerial platforms perform site-specific spraying and seeding with uniform coverage, lowering wastage and operational costs. Multi-tasking robots handle soil preparation, weeding and spraying in a fraction of the time, reducing manual effort and chemical dependency. Intelligent soil monitoring networks provide continuous updates on subsurface conditions, allowing accurate irrigation timing and fertilizer adjustment. Digital mapping and analytics platforms process large-scale spatial and environmental datasets to deliver targeted agronomic insights. Collectively, these solutions improve field efficiency, safeguard resources, and contribute to sustainable production systems while creating measurable gains in both crop output and farm profitability. The progression towards a fully digital agricultural framework in India will depend on strategic policy, infrastructure expansion, and farmer engagement. Rural broadband coverage must be broadened, and low-cost sensor networks should be made accessible to all farming categories. Partnerships among research bodies, private innovators, and grassroots organizations can stimulate rapid development and diffusion of context-specific technologies. Training programmes should focus on practical, hands-on exposure, enabling farmers especially women and youth to manage, troubleshoot, and adapt equipment effectively. Establishing common data standards will help integrate diverse hardware and software, avoiding system incompatibility. Future efforts should emphasize environmentally sound practices, such as minimizing energy use, protecting water resources and lowering emissions, ensuring that digital adoption aligns with national sustainability and climate resilience objectives.

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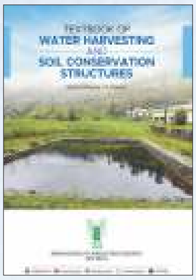

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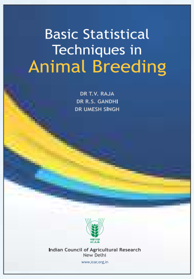

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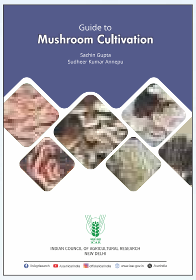

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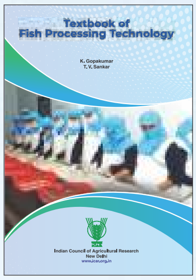

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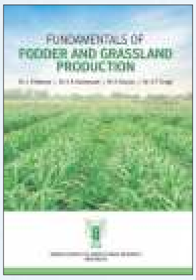

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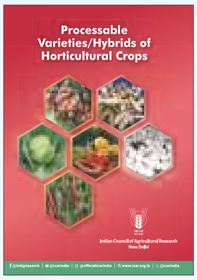

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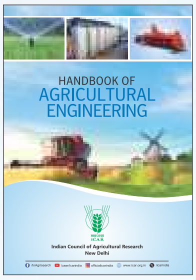

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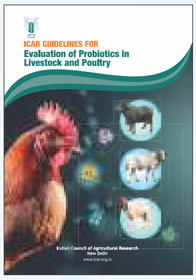

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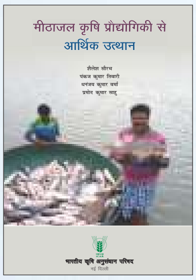

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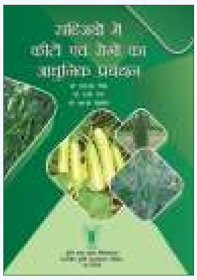

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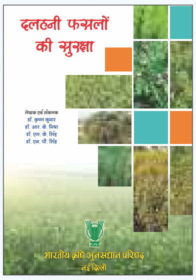

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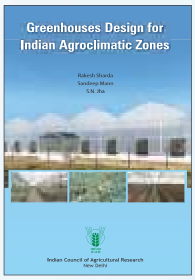

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