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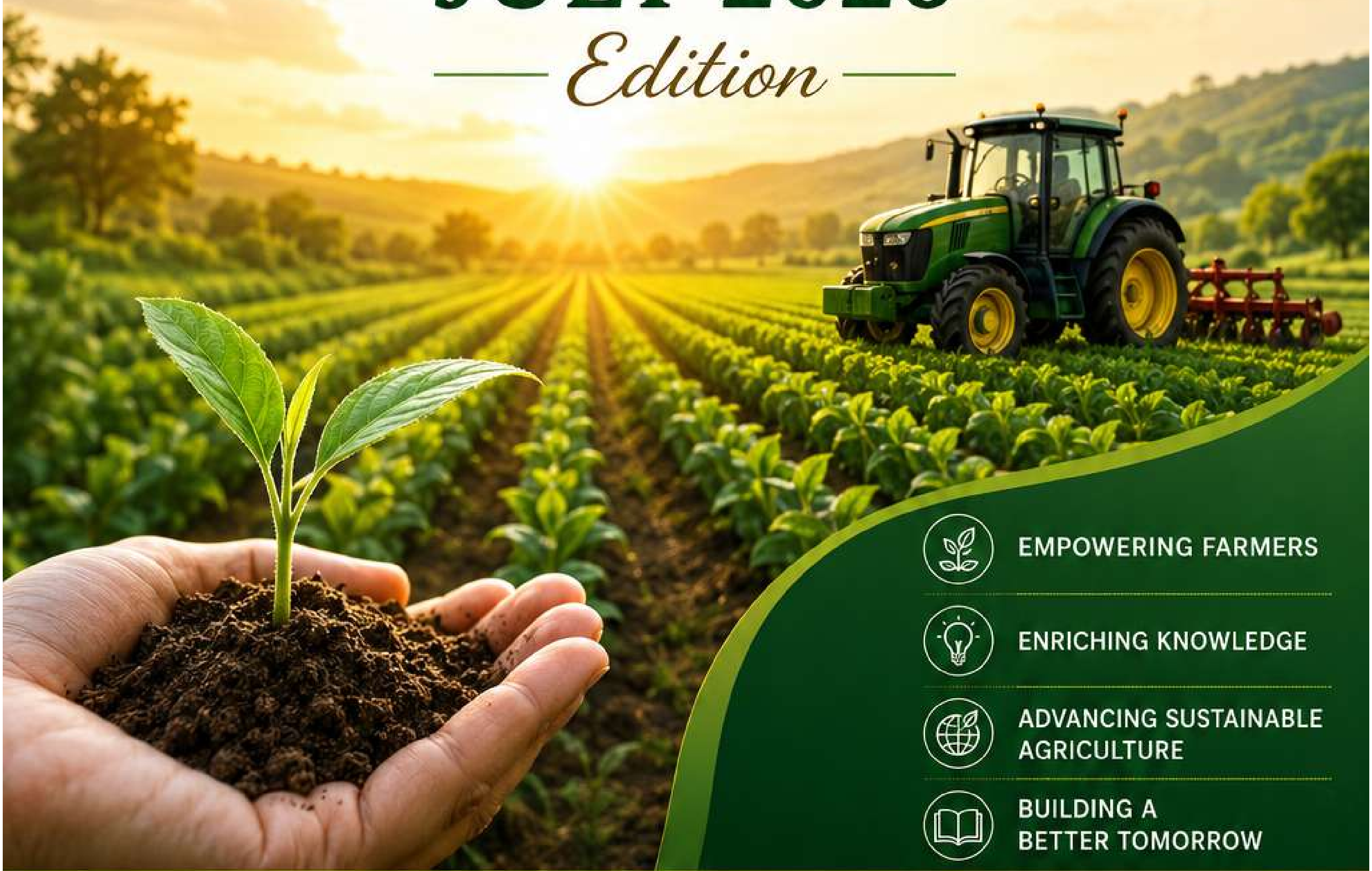

EMPOWERING FARMERS

ENRICHING KNOWLEDGE

ADVANCING SUSTAINABLE AGRICULTURE

BUILDING A BETTER TOMORROW

EMPOWERING FARMERS, ENRICHING AGRICULTURE,
BUILDING A SUSTAINABLE FUTURE

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Empowering Farmers, Enriching Agriculture,
Building a Sustainable Future

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Digital Technologies in Agricultural Extension: Transforming Farmer Advisory Services in the Digital Era

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Abstract

Agricultural extension plays a crucial role in connecting farmers with scientific knowledge, improved technologies, markets, institutions, and other agricultural services. However, conventional extension systems often face challenges such as limited human resources, geographical constraints, delayed information delivery, and inadequate personalization of advisory services. The rapid development of digital technologies has created new opportunities to address these challenges and transform the way agricultural knowledge and services are delivered. Technologies such as smartphones, mobile applications, social media, artificial intelligence (AI), machine learning, Internet of Things (IoT), remote sensing, geographic information systems (GIS), drones, digital platforms, cloud computing, and blockchain are increasingly being integrated into agricultural extension. The review concludes that digital technologies should complement rather than completely replace conventional extension systems. A blended extension approach integrating digital tools with human interaction can provide a more inclusive, responsive, and farmer-centred agricultural extension system.

Keywords: Digital agriculture, agricultural extension, ICT, artificial intelligence, mobile technology, precision agriculture, e-extension, farmers

1. Introduction

Agricultural extension has traditionally served as an important mechanism for transferring agricultural knowledge, technologies, skills, and innovations from research institutions and experts to farmers. Extension systems contribute to improving farm productivity, strengthening farmers' decision-making abilities, promoting sustainable agricultural practices, and linking producers with markets and institutions. However, changing agricultural conditions and the increasing complexity of farming have created new demands for extension services.

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Farmers today require timely information on weather conditions, crop varieties, pest and disease management, input availability, market prices, government schemes, financial services, climate risks, and emerging technologies. Conventional face-to-face extension approaches alone may not always be capable of meeting these rapidly changing information needs, particularly when extension personnel have to serve large and geographically dispersed farming populations.

The development of Information and Communication Technologies (ICTs) has significantly changed the agricultural information environment. The widespread availability of mobile phones, internet connectivity, digital platforms, social media, satellite data, and artificial intelligence has opened new possibilities for delivering extension services. Digital extension, commonly referred to as e-extension or ICT-enabled extension, allows information to be disseminated rapidly and can facilitate two-way communication between farmers, extension personnel, researchers, private organizations, and other stakeholders.

The digital transformation of agriculture has therefore shifted extension from a predominantly linear model of technology transfer towards a more interactive, participatory, and data-driven system. Digital technologies can support not only information dissemination but also diagnosis, decision-making, monitoring, learning, networking, and market integration.

2. Concept of Digital Agricultural Extension

Digital agricultural extension refers to the use of digital technologies and communication platforms to provide agricultural knowledge, advisory services, capacity building, and other extension-related services to farmers and rural communities.

Unlike traditional extension, where information is often delivered through physical meetings, demonstrations, field visits, and printed materials, digital extension can provide information through smartphones, websites, mobile applications, social media, messaging services, call centres, videos, chatbots, online courses, and digital farmer platforms.

Digital extension can be understood through three major functions:

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1. **Information dissemination** – providing farmers with timely information on crops, livestock, weather, markets, schemes, and technologies.
2. **Interactive advisory services** – enabling farmers to communicate directly with experts, extension personnel, and other farmers.
3. **Data-driven decision support** – using farm, weather, soil, satellite, and market data to generate location-specific and customized recommendations.

The effectiveness of digital extension depends not only on technological infrastructure but also on the quality, relevance, accessibility, credibility, and usability of the information provided.

3. Major Digital Technologies Used in Agricultural Extension

3.1 Mobile Phones and Mobile Applications

Mobile phones have become one of the most accessible digital tools for agricultural extension. Smartphones enable farmers to access agricultural applications, weather forecasts, market information, advisory messages, videos, and government services.

Mobile applications can provide crop-specific recommendations covering sowing, irrigation, nutrient management, pest control, harvesting, and post-harvest activities. Applications can also enable farmers to upload photographs of diseased crops and receive diagnostic assistance.

The major advantage of mobile-based extension is its ability to provide information at the farmer's convenience without requiring physical visits to extension offices.

3.2 Social Media and Digital Communities

Social media platforms have emerged as important channels for agricultural communication. Platforms such as YouTube, Facebook, WhatsApp, Instagram, and other online communities can facilitate rapid dissemination of agricultural information.

Agricultural universities, government departments, farmer organizations, agribusiness companies, experts, and progressive farmers increasingly use social media to share videos, demonstrations, success stories, weather advisories, and information about government programmes.

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Video-based communication is particularly useful because it can demonstrate agricultural practices visually. Farmers can observe techniques such as grafting, pruning, nursery management, compost preparation, machinery operation, and pest management rather than relying solely on written instructions.

However, social media also presents challenges related to misinformation, unverified recommendations, commercial bias, and information overload. Therefore, strengthening digital information literacy among farmers is essential.

3.3 Artificial Intelligence and Machine Learning

Artificial intelligence is emerging as an important technology for next-generation agricultural extension. AI-based systems can analyse large volumes of agricultural, climatic, soil, market, and farm-management data to generate recommendations.

AI applications can support:

- Crop and disease identification
- Pest and disease diagnosis
- Weather-based advisories
- Crop yield prediction
- Irrigation recommendations
- Soil and nutrient management
- Market forecasting
- Personalized farmer advisory services
- Agricultural chatbots and virtual assistants

AI-powered conversational systems can potentially provide farmers with immediate responses to routine agricultural questions. Image recognition technologies can also assist in identifying crop diseases from photographs.

Nevertheless, AI-based extension systems must be developed using reliable agricultural datasets and validated by subject-matter experts. Poor-quality data or inappropriate algorithms may result in inaccurate recommendations.

3.4 Internet of Things (IoT)

IoT connects agricultural sensors and devices to digital networks. Sensors can collect real-time information about soil moisture, temperature, humidity, rainfall, crop conditions, and other farm parameters.

For extension services, IoT can facilitate data-driven recommendations. For example, soil-moisture sensors can provide information that supports irrigation decisions, while environmental sensors can help identify conditions favourable for certain pests and diseases.

IoT is particularly relevant to precision agriculture and protected cultivation, although cost and technical requirements can limit its adoption among small and marginal farmers.

3.5 Remote Sensing, GIS and Satellite Technology

Remote sensing and Geographic Information Systems (GIS) enable the collection and analysis of spatial information about agricultural land. Satellite imagery can be used to monitor crop growth, drought conditions, land-use changes, vegetation health, and crop damage.

Extension agencies can use geospatial technologies to identify areas affected by drought, floods, pests, diseases, or other climatic stresses and provide targeted advisories.

The integration of remote sensing with field-level information can improve the spatial precision of agricultural extension and support more efficient planning of extension interventions.

3.6 Drones

Agricultural drones equipped with cameras and sensors can collect high-resolution information about crops. They can support crop monitoring, plant health assessment, pest and disease identification, and assessment of nutrient or water stress.

Drones can also be used for demonstrations and extension training, allowing farmers to observe emerging agricultural technologies. However, regulatory requirements, equipment costs, technical expertise, and maintenance can limit widespread adoption.

3.7 Digital Learning and E-Extension Platforms

Digital platforms provide opportunities for continuous learning among farmers, extension workers, students, and agricultural professionals. Online courses, webinars, digital libraries, podcasts, videos, and virtual demonstrations can support capacity building.

Digital learning is particularly valuable when physical training programmes are difficult to organize because of distance, time, cost, or emergencies. It also enables farmers to revisit learning materials whenever required.

3.8 Blockchain and Digital Market Technologies

Blockchain technology has potential applications in agricultural value chains through traceability, transaction recording, certification, and supply-chain transparency.

Although blockchain is still emerging in agricultural extension, it could contribute to improving farmers' access to reliable information about product origin, quality standards, certification, and market transactions.

4. Applications of Digital Technologies in Agricultural Extension

Digital technologies have applications throughout the agricultural production cycle.

Area	Digital application
Crop planning	Digital crop calendars and decision-support systems
Weather	Forecasts, alerts and climate advisories
Soil management	Digital soil information and nutrient recommendations
Pest management	Image-based diagnosis and pest alerts
Irrigation	Sensor-based irrigation recommendations
Farm machinery	Digital training and machinery information
Markets	Real-time prices and digital market platforms
Government schemes	Online registration and scheme information

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Capacity building	Webinars, videos and online courses
Farmer networking	WhatsApp and social media communities
Disaster management	Satellite monitoring and early-warning systems
Financial services	Digital payments and financial information

5. Digital Technologies and the Future of Extension Workers

Digital transformation does not necessarily mean replacing extension personnel. Instead, the role of extension workers is likely to evolve.

The extension worker of the future may increasingly function as a **digital facilitator, knowledge broker, technology navigator, and trusted advisor**. Extension personnel can help farmers interpret digital recommendations, verify online information, connect with experts, and select technologies appropriate to their farming conditions.

A blended model combining digital communication with face-to-face interaction may therefore be more effective than a purely digital system.

For example, an extension worker can use digital platforms to identify farmers' problems, provide preliminary information, and organize targeted field visits where necessary. This can make extension services more efficient while retaining the trust and local knowledge associated with human interaction.

6. Recommendations for Strengthening Digital Agricultural Extension

For digital technologies to contribute meaningfully to agricultural development, the following measures are important:

1. **Develop farmer-centred digital platforms** based on actual information needs.
2. **Promote local-language and voice-based content** for greater accessibility.
3. **Strengthen digital literacy** among farmers and extension personnel.

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4. **Validate digital advisories** through agricultural universities, research institutions, and qualified experts.
5. **Combine digital and conventional extension methods** rather than treating them as alternatives.
6. **Improve rural digital infrastructure**, particularly internet connectivity and access to affordable devices.
7. **Develop strong data governance mechanisms** to protect farmers' privacy and data rights.
8. **Promote women-inclusive digital extension programmes** to reduce gender-related digital gaps.
9. **Support small and marginal farmers** through affordable and scalable digital solutions.
10. **Build partnerships** among government agencies, universities, startups, private organizations, farmer organizations, and technology companies.

7. Conclusion

Digital technologies are reshaping agricultural extension by making information more accessible, timely, interactive, personalized, and data-driven. Mobile phones, social media, artificial intelligence, IoT, remote sensing, GIS, drones, and digital learning platforms can significantly strengthen the capacity of extension systems to respond to farmers' evolving information needs.

However, technological availability alone cannot guarantee successful digital extension. The digital divide, limited literacy, language barriers, misinformation, infrastructure constraints, affordability, data privacy, and lack of institutional capacity remain significant challenges. Digital transformation must therefore be guided by principles of inclusiveness, accessibility, reliability, farmer participation, and responsible data use.

The future of agricultural extension is likely to be neither completely traditional nor completely digital. Instead, a **hybrid extension model**, in which digital technologies complement the knowledge, trust, and field presence of extension professionals, offers considerable potential. By integrating human expertise with digital intelligence, agricultural extension can become more responsive, scalable, inclusive, and resilient, ultimately contributing to improved farm livelihoods and sustainable agricultural development.

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NATURAL FARMING VS ORGANIC FARMING

Understanding the Difference

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Abstract

As Indian agriculture searches for alternatives to input-intensive chemical farming, two terms are increasingly used, often interchangeably and often incorrectly, to describe the way forward: organic farming and natural farming. While both reject synthetic fertilisers and pesticides, they differ sharply in philosophy, input use, cost structure, and scientific standing. This article traces the origins of each approach, compares their core principles and practices side by side, reviews the evidence on yield and soil health, and examines how Indian policy through schemes such as the Paramparagat Krishi Vikas Yojana and the Bharatiya Prakritik Krishi Paddhati is beginning to distinguish between the two. It closes by considering what farmers should weigh before choosing either path, and where extension education can help them make that choice on solid ground.

Introduction :

Walk into almost any farmer training program in India today, and you are likely to hear both terms within the same hour: organic farming and natural farming are frequently used as though they mean the same thing. They do not. Both movements grew out of a shared unease with the chemical-intensive model that the Green Revolution left behind, and both promise healthier soil, safer food, and lower dependence on purchased inputs. But beneath that shared starting point lie two genuinely

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different philosophies of what farming should look like, how much it should cost, and how much of nature's own processes a farmer should rely on rather than manage.

QUICK FACTS

- Organic farming as a certified system dates back to the early-to-mid twentieth century, formalized globally through bodies such as IFOAM in the 1970s.
- Natural farming's most influential early proponent was the Japanese farmer-philosopher Masanobu Fukuoka, whose "do-nothing" approach questioned even organic inputs.
- In India, natural farming is promoted nationally under the Bharatiya Prakritik Krishi Paddhati (BPKP), while organic farming is supported under the Paramparagat Krishi Vikas Yojana (PKVY).
- Andhra Pradesh runs the world's largest natural farming program, now known as the Andhra Pradesh Community-managed Natural Farming (APCNF) initiative.

What Is Organic Farming?

Organic farming is, at its core, a substitution-based system. It replaces synthetic fertilizers with compost, farmyard manure, vermicompost, and other organic amendments, and replaces synthetic pesticides with biological or botanical alternatives such as neem-based formulations. Crucially, organic farming is defined as much by what it excludes synthetic chemicals, genetically modified organisms, and growth hormones as by what it actively practices. It operates within a well-established certification framework, governed in India by the National Program for Organic Production (NPOP), which allows certified produce to carry a recognized organic label and command a price premium in domestic and export markets.

Because organic farming still relies on external inputs, even if those inputs are organic rather than synthetic, it requires a functioning supply chain for compost, bio-fertilizers, and organic-approved pest control products. This makes it, in many respects, a more capital- and labor-intensive system than conventional farming during the transition years, before soil biology recovers enough to reduce the need for purchased amendments.

What is Natural Farming?

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Natural farming starts from a more radical premise: that healthy soil already contains everything a crop needs, and that the farmer's job is to protect and activate that biology rather than feed the crop directly, even with organic inputs brought in from outside the farm. The approach traces back to Masanobu Fukuoka's experiments in Japan, which emphasized minimal intervention, no tillage, no external fertilizer of any kind, no pesticides, and no weeding beyond natural ground cover management.

In its widely practiced Indian form, popularized as Zero Budget Natural Farming (ZBNF) and now more formally branded as the Bharatiya Prakritik Krishi Paddhati, natural farming centers on a small set of low-cost, farm-produced preparations: Jivamrita, a fermented mixture of cow dung, cow urine, jaggery, pulse flour, and soil, used to inoculate the field with beneficial microorganisms; Beejamrita for seed treatment; mulching to conserve soil moisture; and Waaphasa, a principle of maintaining soil aeration and moisture balance rather than continuous irrigation. The word “zero budget” refers specifically to the absence of purchased external inputs — all preparations are meant to be made on-farm using local cattle and farm resources.

Side by Side: Comparing the Two Approaches

The table below sets out the core points of divergence. Reading it against the shared ground both systems occupy- rejection of synthetic agrochemicals, emphasis on soil health, and a long-term view of farm sustainability- helps clarify why the two are so often confused despite being fundamentally different in method.

Aspect	**Organic Farming**	**Natural Farming**
Core philosophy	Substitute synthetic inputs with organic ones	Minimise external inputs; activate native soil biology
External inputs	Compost, bio-fertilisers, organic pesticides (often purchased)	Farm-produced preparations (Jivamrita, Beejamrita) from local cattle
Certification	Formal NPOP/third-party certification available	No standardised certification system yet in most states

Aspect	Organic Farming	Natural Farming
Cost profile	Higher input cost, especially during transition	Very low cash input cost; higher labour requirement
Tillage	Conventional tillage generally continues	Minimal or zero tillage strongly emphasised
Scientific evidence base	Extensively researched over decades globally	Growing but still comparatively limited and contested
Government scheme (India)	Paramparagat Krishi Vikas Yojana (PKVY)	Bharatiya Prakritik Krishi Paddhati (BPKP)
Market positioning	Established premium and export markets	Emerging market; premium less standardised

What the Evidence Actually Shows

Both systems have their advocates and their critics, and the honest picture is more nuanced than either camp's promotional material tends to suggest. Long-term organic farming trials, some running for several decades, have generally shown that organic systems can match conventional yields for certain crops, particularly pulses and some horticultural crops, while consistently improving soil organic carbon, water-holding capacity, and biodiversity indicators. Yield penalties tend to be more pronounced for cereals, especially in the first several years of transition before soil fertility rebuilds.

Natural farming's evidence base is younger and more contested. Independent multi-year assessments of India's natural farming programmes have found promising results on input cost reduction and, in several cases, comparable yields to conventional farming after an adjustment period, but the scientific community remains divided on whether Jivamrita and similar preparations can, on their own, supply the nutrient volumes that intensive cropping systems require over the long term, particularly for nitrogen and potassium in nutrient-depleted soils. Much of the strongest natural farming

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data so far comes from state-run programmes rather than independent, peer-reviewed long-term trials, which is a gap researchers and universities are actively working to close.

DID YOU KNOW?

- Zero Budget Natural Farming was renamed Bharatiya Prakritik Krishi Paddhati at the national level partly to distinguish it clearly from certified organic farming in policy documents.
- A single adult cow's dung and urine, under ZBNF principles, is claimed to be sufficient to prepare enough Jivamrita for roughly 30 acres a figure still debated among agricultural scientists.
- Sikkim became India's first fully organic state in 2016, following a 2003 policy commitment, illustrating that state-scale conversion is achievable with sustained political backing.

The Economics: Cost, Yield, and Farmer Income

For most farmers, the deciding factor is rarely philosophical; it is economic. Both systems change a farm's cost structure in ways conventional chemical farming does not, and understanding those changes matters more than debating which system is more "natural" in principle. Organic farming typically raises certification and input costs in the short run, since compost, bio-fertilizers, and approved biopesticides are still purchased inputs, even if their environmental footprint is lower than synthetic alternatives. This higher cost is generally offset over time by premium pricing in certified markets, but that premium depends entirely on a farmer's ability to access those markets, something not guaranteed for smallholders far from urban centers or export supply chains.

Natural farming's economics work differently. Because Jivamrita, Beejamrita, and similar preparations are made on-farm from a farmer's own cattle and locally available materials, the cash outlay for inputs drops sharply, often to a small fraction of conventional costs. What natural farming shifts instead is the labor burden: preparations must be made fresh at regular intervals, applied carefully, and monitored closely in the early seasons while soil biology adjusts. For farm households with sufficient family labour and cattle already on hand, this trade-off can meaningfully improve net income even without a price premium. For households short on labour or without livestock, the same trade-off can make natural farming impractical regardless of its lower cash cost.

Yield trajectories under both systems tend to follow a similar pattern: a dip during the first two to three transition years as soil biology and farmer practice adjust, followed by yields that stabilize at

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or near conventional levels for many crops, with some crops, particularly nutrient-demanding cereals in already-depleted soils, showing more persistent yield gaps under natural farming in the available independent studies. This transition period is where farmer dropout is most common, which is why financial bridging support during conversion, whether through government schemes or market-linked contracts, has proven important for sustained adoption under both approaches.

What Happens Beneath the Surface: Soil Biology in Focus

Both systems ultimately stake their claims on soil biology, though they approach it from different angles. Organic amendments such as compost and farmyard manure work primarily by adding organic matter and a broad spectrum of nutrients directly to the soil, which in turn feeds and diversifies the microbial community over time. This is a relatively well-understood, decades-studied process, with clear evidence linking sustained organic matter addition to improved soil structure, water retention, and microbial biomass.

Natural farming's Jivamrita approach works differently in theory: rather than adding significant nutrient volume, it aims to inoculate the soil with a concentrated dose of beneficial bacteria and fungi, on the premise that this microbial activity will unlock nutrients already present in the soil — from mineral weathering, atmospheric nitrogen fixation, and decomposing crop residue — more efficiently than before. Early research on this mechanism shows promising increases in measured soil microbial activity in some trials, but researchers still debate whether inoculation alone can sustain nutrient supply at the volumes intensive cropping requires without any additional organic matter input, particularly in soils that have been under chemical-intensive cultivation for many years and have correspondingly depleted native fertility.

Voices from the Field: Two State Experiences

Andhra Pradesh - Scaling Natural Farming

The Andhra Pradesh Community-managed Natural Farming program is widely cited as the largest natural farming initiative anywhere in the world, working with several lakh farmers across the state through a community-institution model built on women's self-help groups. Farmer-to-farmer training, rather than top-down extension alone, has been central to its spread; experienced natural

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farming practitioners' mentor newer adopters, lending the credibility that comes from a visible, local success story rather than a distant research station demonstration.

Sikkim - The Organic State Model

Sikkim's transition to full organic status followed a different path: a sustained, state-led policy commitment spanning over a decade, phasing out chemical fertilizer subsidies while building organic input supply chains and certification support in parallel. The state's experience underscores that organic conversion at scale is less a matter of farmer willingness alone and more a matter of consistent institutional support sustained across multiple political and budget cycles.

Common Ground: Where Both Systems Agree

For all their differences, organic and natural farming share a set of underlying commitments worth naming explicitly, since these are often what farmers and consumers actually care about most — regardless of which specific method is used to get there.

- Elimination of synthetic pesticides and chemical fertilizers from the field
- Emphasis on soil health as the foundation of long-term productivity, not merely a byproduct of it
- Preference for crop diversity, intercropping, and reduced monoculture dependence
- Reduced farmer exposure to hazardous agrochemicals during application
- A long-term, multi-season view of farm sustainability over short-term yield maximization

Challenges Facing Both Approaches

Neither system has an easy path to mainstream adoption. Organic farming's certification process is often too costly and paperwork-heavy for smallholders to navigate without institutional support, and the yield dip during the multi-year transition period can be financially punishing for farmers without a savings buffer or transition subsidy. Natural farming's low cash-input promise is attractive, but its heavy reliance on labour for preparing and applying Jivamrita and Beejamrita regularly, maintaining mulch, and monitoring fields more closely can be a binding constraint for households already short on labour, particularly where family members have migrated for non-farm work.

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Both systems also face a common market-side challenge: consumer willingness to pay a premium remains concentrated in urban, higher-income segments, and without robust certification or branding, farmers practicing either method often end up selling into the same undifferentiated market as conventional produce, capturing none of the price premium their additional effort might otherwise justify.

Choosing Between Them: What Farmers Should Weigh

Neither organic nor natural farming is universally "better"; the right choice depends heavily on a farm's specific starting conditions. Farmers with reliable access to livestock and family or hired labour, and who are farming in regions where cattle-based inputs are culturally and practically feasible, may find natural farming's low cash-cost model genuinely attractive. Farmers targeting export or premium urban markets, and who can absorb the certification cost and transition-period yield dip, may find organic certification's established market infrastructure a better fit. In practice, many Indian farmers are experimenting with hybrid approaches using natural farming preparations alongside limited organic inputs, rather than adopting either system in its textbook-pure form.

Extension education has an important role to play in helping farmers make this choice with clear eyes rather than following whichever approach is being most actively promoted in their district that season. Balanced, evidence-based advisory support, rather than promotional messaging favoring one system over the other, gives farmers the information they need to match the method to their own land, labor, and market access.

Conclusion

The debate between organic and natural farming is often framed as a contest to be won, but the more useful framing may simply be one of fit. Both approaches represent a genuine departure from chemical-intensive agriculture, and both have demonstrated real success stories at meaningful scale in India, Sikkim for organic, Andhra Pradesh for natural farming. What matters most for the farmer standing in a field trying to decide between them is not which system carries the more compelling name, but which one matches the resources, labour, market access, and risk tolerance of that specific farm. As research on both systems matures, extension services that can offer that kind of grounded, farm-specific guidance, rather than one-size-fits-all advocacy, will do the most to help Indian agriculture move sustainably beyond its chemical-intensive past.

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Digital Agricultural Extension Connecting farmers with knowledge through Technology

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Abstract

Agricultural extension has always been the bridge between the laboratory and the field, translating research findings into practices that farmers can adopt with confidence. For most of the twentieth century, this bridge was built and maintained almost entirely by human intermediaries: extension officers cycling between villages, Krishi Vigyan Kendra scientists holding field days, and farmer-to-farmer word of mouth. That model is now being reshaped by digital technology. Mobile advisory services, artificial-intelligence chatbots, satellite-based crop monitoring, drone imagery, and integrated digital public infrastructure are collectively redrawing how knowledge travels from research institutions to farm gates. This article traces the evolution of agricultural extension from its conventional roots to its emerging digital form, examines the principal tools and platforms driving this shift, reviews India's flagship digital agriculture initiatives and field-level outcomes, and weighs the opportunities against the persistent challenges of connectivity, digital literacy, and last-mile trust. It closes with a set of practical recommendations for extension functionaries, policymakers, and agri-tech developers seeking to make digital extension both scalable and genuinely farmer-centric.

Introduction

Ramesh, a cotton grower in a semi-arid district, once waited weeks for an extension officer to visit his village before he could get an opinion on a pest outbreak spreading through his field. Today, a smartphone photograph and a two-minute wait for an AI-based diagnosis have replaced that wait.

This shift, repeated across millions of farms, marks one of the quieter but most consequential transformations in modern agriculture. Extension services exist to close the gap between what science knows and what farmers practice, and that gap has historically been widened by geography, staffing shortages, and the sheer diversity of agro-climatic conditions across a country as vast as India.

The classical Training and Visit (T&V) system, built on scheduled officer visits and a fixed extension worker-to-farmer ratio, served India well during the Green Revolution years but has struggled to keep pace with a farming population that now exceeds the capacity of any conceivable cadre of human extension agents. Official estimates have long placed the effective ratio of extension personnel to farm households at a level far short of what intensive, personalized advisory work would require. Digital technology does not eliminate the need for human expertise, but it multiplies its reach: a single agronomist's advice, once encoded into a chatbot or an advisory app, can reach lakhs of farmers simultaneously, in their own language, at the moment they need it rather than at the next scheduled visit.

This article is organized around three questions that matter to practitioners: what does digital extension actually consist of, what is already working on the ground, and what stands between the current pilots and truly universal, equitable access. The discussion draws on recent national programmes and field initiatives to keep the analysis grounded in practice rather than in aspiration alone.

1. The Changing Face of Agricultural Extension

Agricultural extension has moved through several identifiable phases. The colonial and early post-independence period relied on demonstration plots and itinerant agricultural officers. The Green Revolution era institutionalized the Training and Visit system, standardizing the frequency of officer-farmer contact. The 1990s and 2000s saw a partial retreat of the public extension machinery alongside the rise of private input dealers as informal sources of advice, a trend that research repeatedly flagged as a source of both useful information and, at times, commercially biased recommendations. The present phase, still unfolding, is defined by three simultaneous developments: near-universal rural mobile phone penetration, falling data costs, and the maturing of artificial intelligence tools capable of processing images, speech, and satellite data at a scale no human cadre could match.

1.1 Why the Conventional Model Struggled to Scale

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- A persistently thin ratio of trained extension personnel to the number of operational farm holdings, particularly in remote and hilly districts.
- Delayed, generic advice that could not account for field-specific soil, weather, and pest conditions on any given day.
- Limited feedback loops, so research institutions rarely learned in real time which recommendations were or were not being adopted.
- Language and literacy barriers that made printed extension literature inaccessible to a significant share of farm households.

Digital extension does not claim to solve every one of these constraints outright, but it directly targets the ones rooted in distance, timing, and scale, precisely the constraints that human-only systems find hardest to overcome.

2. The Pillars of Digital Agricultural Extension

Digital extension is not a single technology but a stack of complementary tools, each suited to a different stage of the farming decision cycle from what to plant, to how to protect the crop, to when and where to sell the harvest. Table 1 summarises the principal categories in use today.

Category	**Representative Tools**	**Primary Use for Farmers**
Mobile advisory & voice services	IVR helplines, SMS alerts, WhatsApp bots, call-centre advisory	Weather forecasts, sowing windows, mandi (market) prices, government scheme information
AI-based diagnostic and chat tools	Image-based pest and disease identifiers, multilingual AI chatbots	Instant diagnosis of crop stress, pest, or nutrient deficiency from a photograph
Remote sensing & GIS	Satellite crop-health maps, decision-support dashboards	Crop area estimation, yield forecasting, drought and flood risk mapping

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Category	Representative Tools	Primary Use for Farmers
Drones and IoT sensors	Spraying drones, soil-moisture sensors, automated weather stations	Precision input application, real-time field-level monitoring
Digital public infrastructure	Unified farmer ID and land-record systems, digital crop survey tools	Seamless access to subsidies, credit, insurance, and targeted advisory
E-marketplaces & fintech	Online mandis, digital payment and micro-credit platforms	Price discovery, direct market linkage, reduced dependence on intermediaries

What distinguishes the current wave from earlier e-governance efforts is integration. A decade ago, a weather SMS service, a market-price website, and a soil-testing scheme typically operated as unconnected silos. Today's platforms increasingly link a farmer's identity, land record, crop data, and advisory history into a single digital profile, allowing recommendations to become progressively more personalized the longer a farmer stays engaged with the system.

3. India's Digital Agriculture Mission: A Closer Look

India's Digital Agriculture Mission, anchored around the AgriStack digital public infrastructure, illustrates how a national programme is attempting to knit these pillars together. AgriStack is built around a unique Farmer ID linked to land records, livestock ownership, and crops cultivated, giving each farm household a verifiable digital identity that other services can plug into. The government has targeted issuing roughly eleven crore Farmer IDs by 2026-27, with more than one hundred million expected across the fiscal year, and states are being pressed to accelerate registration.

- **Box 1 — Components of India's Digital Agriculture Mission**
- Farmer ID and land-record linkage under AgriStack, enabling targeted delivery of subsidies, credit, and insurance.
- Mobile-based Digital Crop Survey capturing real-time, plot-level data on crop type and cultivated area.
- Kisan e-Mitra, a multilingual AI chatbot handling thousands of farmer queries daily across eleven regional languages.
- A satellite-and-GIS-based Krishi decision support system used for pest surveillance and evidence-based planning by extension personnel.
- SATHI, a digital platform for end-to-end seed traceability and quality management.
- Bharat Vistaar, a single-call digital companion offering crop advisory, mandi prices, and weather information through one phone number.

Two features of this architecture deserve particular attention from extension educators. First, the Kisan e-Mitra chatbot demonstrates that AI-based advisory can operate at genuinely large scale while remaining linguistically inclusive, handling an average of roughly eight thousand queries a day across eleven languages. Second, the pest surveillance component shows that digital tools are not meant to replace extension personnel but to extend their reach: several thousand extension workers now use satellite-linked surveillance data to detect pest infestations earlier than field visits alone would allow. The mission's stated objectives doubling farmers' income, strengthening climate resilience, and ensuring no farmer is left behind in the digital transition- position technology explicitly as a means to equity rather than merely to efficiency.

4. Digital Extension in Practice: Field Evidence

4.1 Precision Advisory in Sugarcane - Baramati, Maharashtra

A technology-driven sugarcane initiative in the Baramati belt combined satellite insights, precision advisory, and structured farm-management data to guide irrigation, nutrient, and harvest decisions. Industry assessments presented at a recent digital-agriculture forum reported that the intervention delivered close to a fifty percent increase in sugarcane yield in participating fields, alongside measurable improvements in soil fertility attributed to more disciplined, data-informed input use. The case is frequently cited as evidence that digital advisory tools work best when they are contextual and easy to use rather than generic, a point industry practitioner themselves emphasize when describing what made the initiative succeed where earlier blanket advisories had not.

4.2 Large-Scale Crop Monitoring - Western India

In a major farming state in western India, an integrated crop-monitoring platform combining satellite imagery, GIS, remote sensing, artificial intelligence, and mobile technology was deployed across an area approaching two lakh square kilometers. The initiative improved crop forecasting and acreage estimation at a scale that would be impractical to achieve through field enumeration alone, illustrating how remote-sensing-based extension can complement, rather than substitute for, ground-level advisory work.

4.3 State-Level Policy Push - Maharashtra's MahaAgri-AI

Maharashtra's Agricultural Artificial Intelligence Policy (2025-29) marks a shift from scattered district-level pilots toward statewide deployment of farmer-centric AI platforms, including the MahaVistar AI advisory system. The policy signals that digital extension is moving from being an experimental add-on to becoming a core pillar of state agricultural strategy, with implications for how extension curricula and functionary training will need to evolve in the coming years.

5. Benefits of Digital Extension

Dimension	Traditional Extension	Digital Extension
Reach	Limited by staff numbers and travel time	Scales to millions of users simultaneously
Timeliness	Fixed visit schedules; advice can lag the problem	Near real-time alerts and diagnosis
Personalisation	Generalized, village- or block-level advice	Field- and farmer-specific recommendations

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Dimension	Traditional Extension	Digital Extension
Language access	Dependent on local officer's language skills	Multilingual chatbots and voice interfaces
Feedback loop	Weak; adoption data collected sporadically	Continuous usage data informs programme design
Cost per farmer reached	Relatively high, due to staff-intensive delivery	Falls sharply as user base grows

6. Challenges and Risks

Enthusiasm for digital extension should not obscure the real barriers that stand between promising pilots and universal, equitable adoption.

- **Connectivity gaps**: mobile network quality and affordable data access remain uneven across remote, hilly, and tribal regions, limiting real-time use of image- and video-based tools.
- **Digital literacy**: many older and less-educated farmers, and disproportionately women farmers, find app-based interfaces harder to navigate than a voice call or a personal visit.
- **Language and dialect diversity:** even multilingual systems can struggle with the hyper-local dialects in which farmers actually describe their problems.
- **Data privacy and consent:** linking land records, crop data, and personal identity in a single digital profile raises legitimate questions about who can access that data and for what purpose.
- **Advisory quality and bias**: AI recommendations are only as good as the data and agronomic logic behind them; poorly validated models risk giving confidently wrong advice at scale.
- **Trust and the human touch:** farmers often weigh a known local officer's judgment more heavily than an anonymous app, especially for high-stakes decisions such as loan-linked input purchases.

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None of these challenges is a reason to slow the shift toward digital extension; each is instead a design requirement. Systems that pair digital tools with a visible, trusted human layer, extension officers who can explain, verify, and follow up on an app's recommendation, consistently outperform purely automated deployments in farmer satisfaction surveys and adoption rates.

7. The Way Forward

7.1 For Extension Functionaries

- Treat digital tools as an extension of, not a replacement for, the extension officer's role — using freed-up time from routine queries for complex, high-value farm visits.
- Build local-language content libraries in partnership with Krishi Vigyan Kendras so AI advisory reflects genuinely local agronomic conditions.

7.2 For Policymakers

- Prioritize last-mile connectivity infrastructure alongside platform development, since even the best chatbot is unreachable without a signal.
- Establish clear, farmer-consent-based data governance frameworks for AgriStack and similar unified farmer-data systems.
- Invest in digital literacy campaigns specifically designed for women farmers and older cultivators, who are otherwise at risk of being left behind.

7.3 For Agri-Tech Developers

- Validate AI advisory models against local trial data before scaling, rather than assuming global or national models transfer directly to every agro-climatic zone.
- Design interfaces around voice and image input first, given continuing gaps in text literacy among target users.

Conclusion

Digital agricultural extension is best understood not as a wholesale replacement of the extension officer but as a force multiplier for expertise that has always been scarce relative to the number of farmers who need it. The evidence emerging from India's Digital Agriculture Mission and from state-

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and initiative-level pilots such as the Baramati sugarcane program suggests that, when designed around real farmer needs and paired with continued human support, digital tools can deliver measurable gains in yield, input efficiency, and timeliness of advice. The task ahead is not to choose between the field visit and the app notification, but to weave them into a single extension system in which technology handles scale and speed while trained professionals continue to handle judgment, context, and trust, the qualities no algorithm can fully

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From Farm to Digital Market: How E-Commerce is Empowering Farmers

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Abstract

For generations, the journey of Indian agricultural produce from farm to consumer ran through a long chain of commission agents, wholesalers, and retailers, with the farmer earning the smallest share at the very start of that chain. Digital marketplaces are beginning to compress this chain. This article examines how government-led platforms such as the National Agriculture Market (e-NAM) and the Open Network for Digital Commerce (ONDC) are digitizing price discovery and market access, how private agri-e-commerce ventures are building direct farm-to-consumer and farm-to-retail channels, and how mobile-based input and advisory marketplaces are changing how farmers buy as well as sell. It reviews the scale of adoption achieved so far, the real gains in transparency and price realization, and the infrastructural, logistical, and digital-literacy barriers that still limit how deep this transformation reaches into rural India. The article closes by considering what would be needed to make digital market access a genuine and durable source of farmer income, rather than a parallel channel used mainly by the already better-connected.

Introduction

Ask any farmer who has sold produce at a local mandi about the experience, and a familiar set of complaints tends to surface: prices set with little transparency, payments delayed by days or weeks, and a chain of middlemen each taking a cut before the produce even leaves the yard. This arrangement has defined Indian agricultural marketing for decades, rooted in a mandi system designed in a different economic era and slow to adapt to the possibilities that digital technology now offers.

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Over the past decade, and with particular acceleration in the last five years, a new layer of digital infrastructure has begun to change this picture. Government platforms have digitized price discovery within the mandi system itself, open digital commerce networks have begun connecting farmer collectives directly to retail buyers, and private e-commerce ventures have built entirely new channels that bypass traditional intermediaries altogether. Together, these developments are reshaping not just where farmers sell, but how much of the final price they actually get to keep.

The Old Chain and Why It Persisted

To appreciate what digital marketplaces are changing, it helps to understand what they are changing from. India's Agricultural Produce Market Committee (APMC) system, established to protect farmers from exploitative private trade, over time developed its own inefficiencies: licensed commission agents operating as gatekeepers, informal price-setting practices that left farmers with limited bargaining power, and a fragmented structure where prices for the same commodity could vary sharply between neighboring districts simply because information did not travel freely between mandis.

For a farmer bringing a truckload of tomatoes or onions to a local mandi, this meant accepting whatever price was on offer that morning, often with no reliable way to know whether a better price existed a hundred kilometers away, and even if they did know, no cost-effective way to reach that better market before the produce spoiled. This information asymmetry, more than any single villain in the chain, has been the structural reason middlemen retained so much bargaining power for so long.

e-NAM: Digitizing the Mandi Itself

The National Agriculture Market, known as e-NAM, represents the government's most ambitious attempt to digitize agricultural trade without dismantling the existing mandi infrastructure. Launched in April 2016, e-NAM works by linking APMC mandis onto a single unified electronic trading platform, allowing traders to bid on produce being auctioned in mandis they may never physically visit, and allowing farmers to access a wider pool of buyers than would ever gather at a single local mandi on a given morning.

The platform's growth over the past decade has been substantial. By March 2026, e-NAM had integrated 1,656 mandis across 23 states and 4 union territories, up from 1,389 as recently as 2024, and had registered over 1.8 crore farmers, 2.73 lakh traders, and 4,724 Farmer Producer Organizations.

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Cumulatively, between 2016 and March 2026, the platform facilitated trade of 13.25 crore metric tonnes of agricultural commodities worth approximately ₹4.84 lakh crore a trade value that has grown markedly in just the past two years, reflecting both wider mandi integration and deeper farmer participation.

Functionally, e-NAM digitizes the entire trade lifecycle: digital gate entry when produce arrives at a mandi, lot creation with unique identifiers, quality assaying, competitive online bidding, real-time price tracking, and direct electronic payment into farmers' bank accounts the last of these particularly significant, since delayed or partial cash payment has long been one of the more quietly damaging features of the traditional mandi system. States must undertake specific APMC Act reforms, permitting e-auction, issuing a single trading license valid statewide, and applying a single-point market fee, before their mandis can integrate with the platform, which explains why adoption has been uneven across states even a decade after launch.

ONDC: Opening Up Digital Commerce Itself

Where e-NAM works within the mandi system, the Open Network for Digital Commerce takes a different approach: rather than building a single platform, ONDC is an open protocol that allows any seller-side and buyer-side application to interconnect, breaking the closed-platform model of large e-commerce companies that control both the sellers listed and the buyers who see them.

For agriculture specifically, ONDC has tried to bring farmer producer organizations directly onto this open network. Within roughly a year of the initiative's April 2023 launch, over 8,000 FPOs had registered with the government in connection with the programme, with more than 5,630 farmer collectives active on the platform trading over 3,100 distinct product varieties figures that point to genuine, if still early-stage, uptake. Value-added services have also begun appearing on the network: farmers can request cropping advice, soil testing, and region-specific crop planning recommendations through the same open architecture used for buying and selling.

It is worth being candid about scale, though. As of early 2026, order volumes moving through ONDC's agricultural listings remain considerably smaller than what flows through established e-commerce platforms, and most farmer collectives currently treat it as a supplementary channel often run alongside more familiar tools like WhatsApp-based direct sales rather than a primary revenue

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source. The infrastructure is still being built out, and buyer awareness of ONDC as a place to source farm produce is still developing.

Private Agri-e-Commerce: Building Direct Channels

Alongside these government-backed platforms, a wave of private companies has built agri-e-commerce models that bypass the mandi system almost entirely. Some aggregate fresh produce directly from farmer groups and move it through organized cold-chain logistics to retailers, hotels, and modern grocery chains, compressing what was once a multi-layered supply chain into a handful of steps. Others operate as agri-input marketplaces, selling seeds, fertilizers, and crop protection products directly to farmers through apps and websites, often at more competitive prices than local input dealers, particularly in Tier-2 and Tier-3 towns.

A further category blends advisory and commerce: platforms that combine satellite-based farm advisory with input supply and output procurement in a single app, using farmer data gathered through the advisory service to build credit and insurance products tailored to individual farm conditions. For a farmer, the appeal of these full-stack models lies in dealing with a single trusted platform across the season, rather than negotiating separately with an input dealer, a moneylender, and a mandi commission agent, each with their own terms.

What Farmers Actually Gain

The cumulative effect of these platforms, where adoption has taken hold, shows up in a few concrete ways. Price transparency is the most immediate: a farmer with a smartphone can now check prevailing e-NAM prices in nearby mandis before deciding where to sell, a simple capability that quietly shifts bargaining power away from information asymmetry and toward the farmer. Payment reliability has also improved meaningfully wherever e-NAM's direct electronic payment feature has been adopted, reducing the delayed or partial cash payments that traders have sometimes used to their advantage in the traditional system.

Market access has widened too, particularly for farmer collectives that previously had no realistic way to reach buyers outside their own district. And for FPOs and farmer groups that have successfully listed products on ONDC or built relationships with private supply-chain platforms, direct-to-retail and direct-to-consumer sales offer a share of the retail margin that would otherwise have gone entirely to intermediaries.

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Table 1: Digital Marketplace Types and Farmer Benefits

Platform Type	How It Works	Farmer Benefit
e-NAM	Digitizes trading within existing APMC mandis	Wider buyer pool, transparent bidding, direct payment
ONDC	Open protocol linking FPOs to any buyer app	Access to retail and consumer buyers beyond local market
Full-stack agri platforms	Combines advisory, input supply, and procurement	Single trusted channel, tailored credit and pricing
Agri-input marketplaces	Online sale of seeds, fertilizer, and crop protection	Competitive pricing, wider product choice
Farm-to-retail logistics platforms	Aggregates produce for organized cold-chain delivery	Reduced spoilage, better price realization

The Gap Between Registration and Real Use

A recurring pattern across India's digital agriculture initiatives is a gap between how many farmers or FPOs are registered on a platform and how many are actively, repeatedly using it to their benefit. Registration numbers on e-NAM and ONDC are genuinely impressive, but registering an FPO on a portal is a very different achievement from that FPO consistently securing better prices, season after season, through the platform.

Several practical frictions explain this gap. Many mandis integrated with e-NAM still require produce to be physically present for quality assaying before bidding can occur, limiting the platform's advantage over simply comparing prices informally by phone. Smaller and less well-organized FPOs often lack the catalog-building, packaging, and logistics capacity needed to fulfill orders reliably through ONDC or private platforms, even after they have registered. And many individual farmers, while aware that digital price information exists, still rely on trusted local traders and long-standing relationships when it comes to actually deciding where to sell, trust that digital platforms have not yet fully earned in many communities.

Logistics: The Unglamorous Bottleneck

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Behind every success story of a farmer selling directly to a distant buyer lies an unglamorous but essential layer of logistics: cold storage, packaging, last-mile transport, and quality grading. Digital platforms can create the connection between a farmer and a buyer instantly, but they cannot, by themselves, move a crate of tomatoes from a village in Nashik district to a retailer in Delhi without spoilage that still requires physical infrastructure that India's rural economy has historically underinvested in.

This is where the gains from e-commerce platforms have been most uneven. Regions with reasonably developed cold-chain and transport infrastructure, parts of Maharashtra, Punjab, and Karnataka, for instance, have been able to convert digital market access into real income gains more readily than regions where such infrastructure remains sparse. The Agriculture Infrastructure Fund and similar schemes aimed at building rural warehousing and cold storage are, in this sense, just as important to the success of agri-e-commerce as the digital platforms themselves; a market app is only as useful as the truck, warehouse, and packaging shed that support it.

Digital Literacy and the Question of Who Benefits First

As with most agricultural technology transitions, digital marketplaces have tended to benefit progressive, better-resourced, and more digitally literate farmers first, with smaller and more marginal cultivators following later, if at all. A farmer who already owns a smartphone, has a bank account linked to Aadhaar, and is comfortable navigating an app interface is naturally better positioned to benefit from e-NAM price transparency or ONDC market access than an elderly farmer cultivating a small, rainfed plot with no prior digital experience.

This is not an argument against digital marketplaces, but a reminder that their benefits do not spread automatically or evenly. Extension functionaries, Krishi Vigyan Kendras, and FPO federations have an important role to play here not merely in explaining that these platforms exist, but in providing hands-on, repeated support that helps less digitally confident farmers actually use them, season after season, until the habit takes hold on its own.

Conclusion

Digital marketplaces have not eliminated the middleman from Indian agriculture, and it would be a mistake to expect them to do so entirely in the near term. What they have done is introduce genuine transparency and choice into a system that, for decades, offered farmers very little of either. e-NAM

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has shown that even a system as entrenched as the mandi network can be digitized without being dismantled. ONDC has shown that an open, interoperable approach to digital commerce can bring farmer collectives into the same digital space as large retailers, at least in principle. And private agri-e-commerce ventures have demonstrated that direct farm-to-consumer and farm-to-retail channels are commercially viable at scale.

The unfinished work lies less in building more platforms and more in making sure the infrastructure, logistics, and hands-on support around those platforms keep pace — so that the farmer who benefits from digital market access is not only the one who already had a smartphone, a bank account, and a nearby cold-storage facility, but, gradually, every farmer with produce to sell.

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Livestock Farming: The Second Engine of Rural Prosperity

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Abstract

Livestock farming has emerged as a critical, though historically under-emphasized, pillar of India's rural economy, contributing over 30 percent of agricultural Gross Value Added and providing daily income to millions of smallholders and landless households. This article examines the structural importance of livestock as a complement to crop agriculture, offering income smoothing, risk buffering, and accessible entry points for resource-poor and women-led households. It traces the achievements and unfinished agenda of India's White Revolution, surveys the growing meat, egg, and wool economy, and identifies persistent constraints including feed and fodder scarcity, uneven veterinary coverage, weak breeding infrastructure, and fragmented market access. Drawing on current government schemes such as the Rashtriya Gokul Mission and National Livestock Mission, the article argues for stronger integration between crop-focused and livestock-focused extension delivery, and outlines practical, farmer-adoptable priorities from fodder security to women-inclusive extension design, needed to realize livestock farming's full potential as a second engine of rural prosperity.

Introduction

Ask most people what powers rural India's economy, and the answer that comes to mind first is almost always the crop field: wheat in Punjab, rice in the deltas, cotton in Maharashtra, sugarcane in western Uttar Pradesh. Yet walk into any village at dawn, and you will notice a quieter but equally vital economic engine at work: the milking of buffaloes and cows, the tending of goats and poultry, the feeding of livestock that, for millions of households, provides a more reliable and immediate source of cash than the crop itself.

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Livestock farming is, in a very real sense, India's second engine of rural prosperity — one that runs every single day of the year, unlike crop agriculture, which is bound by sowing and harvest seasons. According to the Department of Animal Husbandry and Dairying, livestock contributes over 5 percent to India's overall Gross Value Added and more than 30 percent to agricultural GVA, a share that has been steadily rising even as the relative contribution of crop farming has declined.

This article makes the case for why livestock deserves far greater attention within agricultural extension systems that have historically been built around crop-centric advisory services, and outlines what an integrated crop-livestock extension approach could look like on the ground.

The Scale of India's Livestock Economy

India holds the distinction of being the world's largest milk producer, a position it has maintained for over two decades since surpassing the United States in the mid-1990s. The 20th Livestock Census recorded a total livestock population exceeding 535 million, including roughly 193 million cattle, 109 million buffaloes, and vast numbers of goats, sheep, and poultry spread across the country's diverse agro-climatic zones.

What makes this scale particularly significant from a rural development perspective is its distribution. Unlike large-scale commercial crop farming, livestock rearing in India remains predominantly a smallholder activity, the National Sample Survey data consistently show that marginal and small farmers, as well as landless rural households, own a disproportionately large share of the country's livestock, particularly small ruminants like goats and sheep, and backyard poultry. For households with little or no land, livestock is often the single most accessible entry point into agricultural income generation.

Why Livestock Matters More Than the Numbers Suggest

The economic case for livestock extends well beyond its headline contribution to GVA. Livestock provides what agricultural economists call 'income smoothing', daily or near-daily cash flow from milk sales that helps households manage routine expenses even during the lean months between crop harvests, when crop income is entirely absent. This function is especially critical for smallholder and marginal farming households operating on thin financial margins.

Livestock also functions as a form of insurance against crop failure. When erratic monsoons, pest outbreaks, or price crashes devastate crop income, livestock, particularly small ruminants that can be sold relatively quickly, often serves as a fallback source of liquidity, a role sometimes described as the farmer's 'walking bank account.' Additionally, livestock and crop farming are deeply interlinked at the farm-system level: draught animals support tillage in areas with limited mechanization, farmyard manure from livestock enriches soil fertility, and crop residues in turn provide a significant share of livestock feed, an integration that lies at the heart of India's traditional mixed farming systems.

The White Revolution and Its Unfinished Agenda

No account of Indian livestock development is complete without Operation Flood, the cooperative dairy development programme launched in 1970 under the leadership of Dr. Verghese Kurien. By linking millions of small milk producers to organized cooperative marketing structures most famously the Amul model in Gujarat, Operation Flood transformed India from a milk-deficit nation into the world's largest producer within a generation, while ensuring that a meaningful share of consumer prices flowed back to producers rather than being captured by intermediaries.

Yet the White Revolution's underlying agenda remains far from complete. India's average milk yield per animal remains well below global benchmarks, constrained by poor genetic quality of indigenous stock in many regions, inadequate access to balanced feed and fodder, and gaps in veterinary and artificial insemination coverage, particularly in remote and hilly districts. Closing this productivity gap rather than simply expanding animal numbers represents the single largest opportunity for increasing dairy incomes without proportionally increasing the land, water, and feed resources required.

Beyond Dairy: The Growing Meat, Egg, and Wool Economy

While dairy dominates public perception of Indian livestock farming, the broader sector encompasses substantial and rapidly growing sub-sectors. India ranks among the world's leading egg producers, with poultry, both commercial broiler operations and backyard flocks, providing an important protein and income source, particularly for women-led household enterprises in rural areas. Government schemes promoting backyard poultry distribution, particularly of improved dual-purpose breeds developed by

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ICAR institutions, have been credited with providing meaningful supplementary income to thousands of rural households, especially in eastern and northeastern states.

Small ruminant farming, goats and sheep, continues to expand, driven by rising domestic meat demand and the relatively low capital and land requirements compared to large ruminant dairying, making it particularly accessible to landless and marginal households. Meanwhile, India's meat export sector, dominated by buffalo meat, has emerged as a significant foreign exchange earner, positioning the country among the world's leading meat exporters even as domestic consumption patterns continue to evolve.

Key Constraints Facing Livestock Farmers

Despite its scale and importance, Indian livestock farming faces persistent structural constraints that extension systems must directly address. Feed and fodder scarcity remains perhaps the most pervasive challenge; India faces an estimated shortage of green fodder, dry fodder, and concentrate feed relative to livestock population requirements, forcing many farmers to rely on nutritionally inadequate feeding practices that suppress both productivity and animal health.

Veterinary service coverage, particularly for preventive care such as vaccination against diseases like Foot-and-Mouth Disease (FMD) and Peste des Petits Ruminants (PPR), remains inconsistent across states, with rural and remote areas frequently underserved relative to peri-urban and commercial dairy belts. Breeding infrastructure, access to quality artificial insemination services and genetically superior breeding stock also vary considerably, contributing to the wide yield gaps observed between progressive commercial dairies and traditional smallholder herds.

Market access presents a further constraint, particularly for meat, wool, and non-cooperative dairy producers who often depend on informal, multi-tiered intermediary chains that capture a disproportionate share of the final consumer price, leaving primary producers with thin margins despite bearing the bulk of production risk and cost.

Table 1. Key Constraints in Indian Livestock Farming and Their Extension Implications

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Constraint	Typical Manifestation	Extension Response Needed
Feed and fodder shortage	Nutritionally inadequate rations, low milk yield	Fodder cultivation demos, silage/hay-making training, feed balancing advisory
Poor breeding access	Low genetic potential, long calving intervals	AI camps, breed improvement programmes, bull registration drives
Limited veterinary coverage	Delayed disease detection, preventable mortality	Mobile veterinary units, para-vet training, vaccination camps
Weak market linkages	Low farmgate prices, price volatility	Dairy cooperative formation, FPO linkage, e-NAM-style livestock market platforms
Low mechanization/labour burden	High drudgery, especially for women	Milking machines, chaff cutters, women-focused SHG training

Women and the Livestock Economy

Livestock farming occupies a distinctive place in the gender dynamics of rural Indian agriculture. Studies conducted by ICAR and various State Agricultural Universities consistently find that women contribute a substantial majority of labour involved in day-to-day livestock care feeding, milking, cleaning, and health monitoring, even in households where men are formally recorded as the primary landholders or farm decision-makers.

This makes livestock-focused extension a particularly powerful lever for women's economic empowerment, provided programmes are deliberately designed to reach women farmers directly rather than routing exclusively through male household heads, as extension services have historically tended to do. Self-help group-based dairy and poultry enterprises, often supported through the National Rural Livelihoods Mission (NRLM) and state-level women's empowerment schemes, have demonstrated that targeted livestock extension can translate directly into women's control over household income, not merely additional unpaid labour.

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Government Schemes Supporting the Sector

Policy support for livestock development has expanded considerably in recent years. The Rashtriya Gokul Mission focuses on conservation and genetic improvement of indigenous cattle breeds, while the National Livestock Mission supports fodder development, breed improvement, and entrepreneurship in poultry, sheep, goat, and piggery farming. The Animal Husbandry Infrastructure Development Fund (AHIDF) provides concessional credit for setting up dairy processing, meat processing, and animal feed plants, aiming to strengthen value chains beyond primary production.

The National Animal Disease Control Programme has pursued large-scale vaccination campaigns against FMD and brucellosis, addressing one of the most direct causes of production loss in Indian livestock. At the state level, many Departments of Animal Husbandry now operate mobile veterinary units and doorstep artificial insemination services, gradually extending coverage into previously underserved rural pockets though considerable geographic unevenness remains.

Fodder Security: A Foundational Priority

Among all the interventions available to extension workers, promoting fodder security may offer the highest return on effort, since inadequate nutrition underlies a large share of the productivity gap between Indian and global livestock yields. Practical, farmer-adoptable interventions include promoting high-yielding fodder varieties such as hybrid napier grass and berseem, encouraging fodder cultivation on field bunds and otherwise unused land, training farmers in silage-making to preserve surplus green fodder for lean seasons, and demonstrating urea-molasses mineral block (UMMB) supplementation to improve the nutritional value of straw-based rations.

Azolla cultivation, a fast-growing aquatic fern that serves as a protein-rich feed supplement, has also gained extension attention in several states as a low-cost, water-efficient option that smallholders can cultivate in small pits even with limited land availability, offering a meaningful supplement to otherwise fiber-heavy traditional rations.

Integrating Crop and Livestock Extension

Perhaps the most important structural shift needed is moving away from the historical separation between crop-focused agricultural extension (delivered through ATMA and KVKs under the agriculture department) and livestock-focused veterinary extension (delivered through a largely

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separate animal husbandry department structure). In practice, farm households do not experience their farm as two separate enterprises, decisions about crop residue use, land allocation for fodder versus cash crops, and labour division between crop and livestock activities are made holistically at the household level.

KVKs, with their broad mandate spanning agriculture, horticulture, and livestock, are well positioned to model this integration, and several have demonstrated success with composite farming system demonstrations that show farmers the combined economics of crop-livestock integration rather than presenting the two as separate advisory silos. Strengthening convergence between ATMA's farmer group mobilization capacity and the technical depth of veterinary and animal husbandry departments could substantially improve the reach and coherence of livestock extension delivery going forward.

A Snapshot Comparison: Crop Income vs. Livestock Income Patterns

For extension workers explaining the complementary role of livestock to farmer groups, it can help to frame the contrast in terms of income timing and risk profile rather than absolute value — since the two enterprises behave very differently across a typical farming year.

Table 2. Contrasting Income Characteristics of Crop and Livestock Farming

Characteristic	Crop Farming	Livestock Farming (Dairy/Poultry)
Income frequency	Seasonal (1–3 payouts/year)	Daily or near-daily
Capital requirement	High (land, seed, inputs)	Lower entry point (esp. small ruminants, poultry)
Weather sensitivity	High	Moderate (mainly via fodder availability)
Suitability for landless households	Low	High
Role in household risk management	Primary income source	Buffer/insurance + steady cash flow

Building Farmer Capacity: What Effective Livestock Extension Looks Like

Translating policy support into farm-level productivity gains depends heavily on the quality and reach of extension delivery. Effective livestock extension programmes typically combine several elements: regular animal health camps that combine vaccination with basic health screening, hands-on training in balanced ration formulation using locally available feed ingredients, demonstration of simple record-keeping practices that help farmers track milk yield and reproductive cycles, and structured exposure visits where farmers observe well-managed dairy or poultry units in their own region.

KVK-led front-line demonstrations on fodder crops, mineral supplementation, and clean milk production practices have shown particular promise in shifting farmer practice, precisely because they allow farmers to observe measurable outcomes on comparable local farms rather than relying on generic technical advice. As with crop extension, the credibility of livestock extension messaging is strongly reinforced when it is delivered by, or visibly endorsed by, respected local farmers rather than through top-down instruction alone.

The Road Ahead

As India's rural economy diversifies and per capita demand for milk, meat, and eggs continues its steady long-term rise, livestock farming is positioned to play an increasingly central role in rural income growth, potentially outpacing crop agriculture in several regions. Realizing this potential, however, depends on treating livestock development with the same seriousness, institutional investment, and extension sophistication historically reserved for crop agriculture.

This means closing productivity gaps through better breeding and nutrition rather than simply expanding herd sizes; strengthening veterinary and market infrastructure in underserved regions; deliberately designing extension programmes to reach women, who form the backbone of day-to-day livestock labour; and breaking down the institutional silos that separate crop and livestock advisory services. Done well, livestock farming can indeed become what its long-term trajectory suggests it is already becoming not a secondary activity alongside crop farming, but a genuine second engine of rural prosperity in its own right.

Conclusion

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Livestock farming is no longer a peripheral rural activity to be addressed as an afterthought within a crop-dominated extension system, it is a foundational pillar of household income, food security, and economic resilience for a large share of India's rural population, and its relative importance is only set to grow. The sector's daily cash flow, low entry barriers for landless and marginal households, and central role in women's economic participation give it a distinctive capacity to reduce rural poverty that crop agriculture alone cannot replicate.

Realizing this potential fully will require sustained investment in feed and fodder security, breeding and veterinary infrastructure, and market linkages, alongside a deliberate institutional shift toward integrated crop-livestock extension delivery. For soil scientists, agronomists, and extension professionals alike, recognizing livestock not as a separate sector but as an integral part of the farming system is an essential step toward more holistic, resilient, and equitable rural development in India.

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Climate Change and Indian Agriculture: Challenges and Practical Solutions

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Abstract

Climate change has emerged as one of the most pressing threats to Indian agriculture, a sector that supports nearly half of the country's workforce and remains heavily dependent on the monsoon and rainfed cultivation. Rising temperatures, erratic rainfall, prolonged droughts, floods, cyclones, and new pest outbreaks are already reducing crop and livestock productivity and destabilizing rural livelihoods. Government assessments indicate that, without adaptation, climate change could substantially reduce annual agricultural incomes, with rainfed and unirrigated regions facing the greatest losses. This article examines the nature of climate change, the reasons for India's high vulnerability, and its major impacts on crops, livestock, and farm households. It then presents a practical toolbox of adaptation measures, climate-smart agriculture, efficient irrigation, stress-tolerant varieties, precision and digital farming, and integrated pest management. Drawing on documented field successes and supportive national policies, it argues that a combination of science, farmer awareness, community action, and sound policy can make Indian agriculture markedly more resilient and sustainable.

Keywords: *climate change, Indian agriculture, climate-smart agriculture, monsoon variability, adaptation, crop resilience, sustainable farming.*

1. Introduction

Agriculture is the backbone of India. It sustains the livelihoods of a large share of the population, anchors the rural economy, and underpins the nation's food and nutritional security. Yet this vast enterprise rests on a delicate foundation the weather. For generations, Indian farmers read the sky to decide when to sow and when to harvest. Today those familiar signals are becoming unreliable. The monsoon arrives late or in violent bursts, wells run dry sooner than before, and heat waves scorch standing crops just weeks before harvest.

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Climate change is no longer a distant scientific forecast; it has entered the fields, orchards, ponds, and cattle sheds of rural India. It appears as a heat wave that shrivels wheat, a cloudburst that drowns paddy, or a pest that colonises regions it never inhabited before. Because so many Indian farmers cultivate tiny plots and depend on rainfall with no assured irrigation, even small shifts in temperature and rainfall can translate into large losses. Understanding this challenge, and knowing what can be done about it, has therefore become one of the most urgent tasks of our time. This article explains the problem in accessible terms and lays out practical, field-tested solutions.

- About 51% of India's net sown area is rainfed. These lands produce nearly 40% of the country's food grains and support the majority of its livestock, yet they are the most exposed to climatic shocks (Economic Survey 2017–18).

2.1 Understanding Climate Change

Weather and climate are often confused, but the distinction is simple. Weather is what happens on a single day: a rainy Tuesday or a hot afternoon. Climate is the long-term average pattern of that weather over many years. Climate change means that this long-term pattern is itself shifting: the world is steadily warming, seasons are drifting from their usual boundaries, and rainfall is becoming more erratic. At the heart of the problem lie greenhouse gases, chiefly carbon dioxide, methane, and nitrous oxide, which trap heat like a thickening blanket around the Earth. Burning fossil fuels, clearing forests, and certain farming practices release these gases in growing quantities, driving global warming. Notably, agriculture is both a victim and a contributor: flooded rice fields, livestock, and heavy fertilizer use emit methane and nitrous oxide, gases that trap far more heat than carbon dioxide (**IPCC, 2022**).

2.2 Why Indian Agriculture Is Highly Vulnerable

India occupies a particularly exposed position for several interconnected reasons:

- ✓ **Monsoon dependence:** The southwest monsoon delivers roughly three-quarters of annual rainfall in just four months; when it falters, the entire cropping calendar is disrupted.
- ✓ **Small and fragmented holdings**: More than 85% of farmers are small or marginal, so a single bad season can push a family into debt.

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- ✓ **Rainfed farming**: Around half the cropland has no assured irrigation and gambles on the sky every season.
- ✓ **Water scarcity:** Falling groundwater tables force farmers to pump ever harder, deepening the crisis.
- ✓ **Limited resources**: Costly seeds, machinery, and protective technologies remain out of reach for many.
- ✓ **Regional variability**: Drought in one region, floods in another, and hailstorms in a third can strike in the same season, each demanding a different response.

2.3 Major Impacts on Agriculture

Climate change advances on many fronts at once. Rising temperatures are the most direct threat: a heat wave during the grain-filling stage that struck northern India in March 2022 shriveled wheat grains and sharply cut yields, while heat stress reduced milk output in dairy animals. Irregular rainfall delays sowing, shortens growing seasons, and triggers flash floods that wash away seed and soil, even as mid-season dry spells quietly strangle healthy-looking crops. Cyclones along the coasts and hailstorms in the north add sudden, brutal blows. Quieter damage accumulates too: repeated floods and droughts degrade the soil, warmer and more humid conditions accelerate pest and disease outbreaks, and erratic weather at harvest causes heavy post-harvest losses. Government simulations project that, without adaptation, rainfed rice yields could fall by around 20% by 2050 and much more by 2080 (Ministry of Agriculture and Farmers Welfare, 2023).

Climate Change Challenge	**Effect on Agriculture**
Rising temperatures & heat waves	Grain shrivelling in wheat, poor fruit set, heat stress and lower milk yield in livestock
Delayed or weak monsoon	Late sowing, shorter crop season, failed germination
Floods & heavy downpours	Waterlogging, seed and soil loss, crop lodging
Prolonged droughts	Wilting, crop failure, falling groundwater in rainfed regions

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Climate Change Challenge	Effect on Agriculture
Cyclones & hailstorms	Sudden flattening of crops, orchard damage, coastal salinity
Warmer, humid conditions	New pest and disease outbreaks, faster insect breeding
Erratic weather at harvest	Post-harvest spoilage, storage losses, quality downgrading

2.4 Crops Most Affected

Every crop has its comfort zone, and climate change is pushing many beyond it. Rice suffers under both water shortage and high night temperatures that reduce grain quality. Wheat is highly sensitive to late-season heat, which shortens grain filling. Maize faces drought at tasseling and new pests such as the fall armyworm. Pulses and oilseeds, grown largely on rainfed land, are hit by erratic rain and temperature swings. Sugarcane strains scarce water, cotton attracts pests like the pink bollworm, apples in the hills lack sufficient winter chilling, and vegetables such as tomato and chilli wilt or drop flowers under heat stress, causing sharp market price swings.

2.5 Impact on Farmers' Livelihoods

Behind every damaged crop is a family. The most immediate wound is income instability a bumper harvest one year, ruin the next compounded by rising cultivation costs for deeper borewells, extra pesticides, and additional irrigation. When farming stops paying, distress migration follows, often leaving villages of the elderly and women who must manage farms alone. Women farmers, already disadvantaged in access to land, credit, and information, carry a particularly heavy burden. For smallholders with no financial buffer, a single failed season can mean debt and food insecurity. Estimates suggest climate change could reduce annual farm incomes by 15–18% on average, and by 20–25% in unirrigated areas, in the absence of adaptation (**Economic Survey 2017–18**).

Farmer's Tip

Never keep all your eggs in one basket. Growing two or three crops, keeping a few animals, and maintaining a kitchen garden spreads risk, if one source fails, the others can carry the family through.

2.6 Practical Solutions for Farmers

For almost every problem climate change creates, practical answers exist. Used together, they can turn a vulnerable farm into a resilient one. Climate-smart agriculture combines several proven techniques: crop diversification and mixed farming to spread risk; agroforestry for shade, fodder, and extra income; and conservation agriculture to protect topsoil and conserve moisture. Healthy soil acts as insurance; regular soil testing through the Soil Health Card enables balanced fertilization, while biofertilizers, organic and natural farming, and mulching rebuild soil life and retain water.

On water, every drop counts: drip and sprinkler irrigation cut waste by half or more, and rainwater harvesting and farm ponds store the monsoon's bounty for dry spells. Weather-based crop planning and stress-tolerant varieties bred for drought, flood, heat, or salinity prevent avoidable losses, while integrated pest management controls new pests with minimal chemicals. Crop insurance cushions farmers when disaster still strikes. Finally, a quiet digital revolution precision agriculture, mobile advisory services, drones, and AI-based tools- helps farmers apply inputs exactly where and when needed.

Practical Adaptation Measure	**Key Benefit for the Farmer**
Drip & sprinkler irrigation	Saves 40–60% water, lowers power cost, improves yields
Rainwater harvesting & farm ponds	Stores monsoon water, recharges groundwater
Crop diversification & mixed farming	Spreads risk, steadies income, improves nutrition
Stress-tolerant varieties	Survive drought, flood, heat and salinity
Soil Health Card & balanced fertilization	Cuts input waste, raises fertility and profit

Practical Adaptation Measure	Key Benefit for the Farmer
Integrated pest management	Controls new pests safely, lowers chemical cost
Digital & precision tools, crop insurance	Guide timely decisions, cushion losses

3. Case Studies: Resilience in Action

Nothing inspires like proof that change is possible. Across India, farmers and whole communities have shown that resilience is a decision, not a dream.

3.1 Hiware Bazar, Maharashtra

Once a drought-scarred, impoverished village, Hiware Bazar transformed itself through disciplined water conservation, harvesting rainwater, building check dams, regenerating watersheds, and restricting water-hungry crops. Dry land turned green, groundwater recharged, and the community lifted itself out of poverty, becoming a national model of collective climate adaptation.

3.2 Community-Managed Natural Farming, Andhra Pradesh

Andhra Pradesh has scaled up community-managed natural farming to reach lakhs of farmers, helping them cut input costs, rebuild soil health, and reduce chemical dependence. Many participating farmers report steadier incomes and crops that better withstand dry spells, a living example of low-cost climate adaptation.

3.3 Organic Sikkim and Conservation Pioneers

Sikkim, India's first fully organic state, together with individual organic and natural-farming pioneers elsewhere, has shown that farming in tune with nature can be both profitable and sustainable. Their soils, rich in organic matter, retain moisture better and recover faster after weather shocks. Field trials of conservation agriculture in rainfed uplands have similarly improved system productivity and profitability.

3.4 NICRA Villages and Farmer Collectives

Under the National Innovations in Climate Resilient Agriculture (NICRA) programme, drought- and flood-tolerant varieties and climate-resilient practices have been demonstrated in

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vulnerable districts across the country. Alongside, water-user groups and farmer producer organizations show that when communities plan together, share water fairly, buy inputs collectively, and sell in bulk, the whole village grows stronger against climate shocks.

4. Policy Support and Government Initiatives

No farmer faces this challenge alone. India has built a wide network of schemes and institutions to help agriculture adapt; knowing about them and using them makes a real difference.

- **National Mission for Sustainable Agriculture (NMSA)**: The flagship effort to build resilience through better soil, water, and resource management.
- **Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)**: Promotes efficient irrigation under the goal of 'more crop per drop', supporting drip and sprinkler systems.
- **Pradhan Mantri Fasal Bima Yojana (PMFBY)**: Affordable crop insurance protecting farmers against losses from natural calamities.
- **Soil Health Card Scheme**: Gives farmers a report card of their soil for wiser fertilization.
- **Paramparagat Krishi Vikas Yojana (PKVY)**: Encourages organic and cluster-based sustainable farming.
- **Digital Agriculture Mission and eNAM**: Build digital infrastructure and connect farmers to buyers nationwide for better prices.
- **Krishi Vigyan Kendras (KVKs) and ICAR–NICRA**: A vast research and extension network developing climate-resilient varieties and training farmers on the ground.

5. Conclusion

Climate change is, without doubt, one of the most serious challenges Indian agriculture has ever faced. It tests the patience, resources, and spirit of millions of farmers who ask for little more than a fair season and a fair price. Yet the story of Indian farming has always been a story of resilience. From the plains of Bundelkhand to the terraces of the Himalayas, farmers have survived droughts, floods, and famines by adapting and standing together.

Today they possess something their ancestors did not: a powerful partnership of scientific knowledge, modern technology, farmer awareness, community strength, and supportive government policy. If these forces are brought together, if a farmer can harvest rainwater, sow a heat-tolerant

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variety, check the forecast on a phone, and know that insurance stands behind the crop, then a changing climate need not spell the end of Indian agriculture. It can instead mark the beginning of a smarter, greener, and more resilient era. The rain may have forgotten its old schedule, but Indian farming is learning to write a new one, and in that determination lies the hope of a nation.

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From Farm to Market: Modern Marketing Strategies for Better Prices

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Abstract

For millions of Indian farmers, the hardest part of farming is not growing the crop but selling it at a fair price. Small quantities, many sellers and few buyers, perishable produce, weak bargaining power, and a long chain of intermediaries often leave the farmer with only a fraction of the price the consumer finally pays. This article explains why farmers so often receive poor prices and sets out modern marketing strategies that can change this. It examines collective marketing through Farmer Producer Organizations and cooperatives, digital and direct marketing channels such as the electronic National Agriculture Market and e-commerce, value addition through grading, processing, packaging and branding, and better use of storage and market timing to avoid distress sales. Drawing on documented successes such as the dairy cooperative movement and supportive national programmes, it argues that when farmers aggregate their produce, reach wider markets, add value, and sell at the right time, they can capture a far larger share of the consumer's rupee and secure more stable and rewarding incomes.

Keywords: *agricultural marketing, farmer producer organizations, e-NAM, value addition, direct marketing, price realization, post-harvest management.*

1. Introduction

A farmer in a village works for months, preparing the land, sowing, watering, weeding, guarding the crop against pests and weather and finally brings a good harvest to the market. There, in a single afternoon, the price he receives is decided by forces largely beyond his control. Too often, he sells in a hurry, to whoever is present, at whatever rate is offered, and returns home with far less than his effort

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deserved. Meanwhile, the same produce reaches the city consumer at several times that price. The difference vanishes somewhere along the way, and rarely into the farmer's pocket.

This gap between what the farmer earns and what the consumer pays lies at the heart of rural distress. It is not mainly a problem of production Indian farmers grow enough, and grow well. It is a problem of marketing: of how, where, when, and to whom the produce is sold. The encouraging news is that this is exactly the kind of problem that modern strategies can solve. By joining together, reaching new markets, adding value, and selling smartly, farmers can claim a much larger share of the final price. This article explains why prices are often poor and lays out the practical marketing strategies that can deliver better returns.

2.1 Why Farmers Often Get Poor Prices

To fix a problem, one must first understand it. Several features of traditional agricultural marketing work against the farmer at the same time.

Marketing Problem	**Why It Hurts the Farmer**
Small, scattered quantities	Individually a farmer has little produce and no bargaining power
Many sellers, few buyers	Local traders can set low prices when farmers have nowhere else to go
Perishable produce	Fruits, vegetables and milk must be sold fast, forcing acceptance of low offers
Lack of information	Farmers rarely know prices in other markets, so they cannot compare
No storage	Without a place to hold produce, farmers sell immediately at harvest, when prices are lowest
Long chain of middlemen	Each intermediary takes a margin, shrinking the farmer's share

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The result is the familiar tragedy of the distress sale the farmer selling at the bottom of the market simply because waiting is not an option. Modern marketing strategies attack each of these weaknesses in turn.

2.2 Understanding the Marketing Chain

Between the field and the family that eats the food lies a chain of hands: the farmer, a village aggregator or commission agent, the wholesale market, the retailer, and finally the consumer. Every link adds some genuine service: transport, sorting, storage, risk-bearing, but every link also takes a share of the price. The longer and more crowded the chain, the smaller the slice left for the person who grew the crop. The core aim of modern marketing is therefore simple: either shorten the chain, so the farmer sells closer to the consumer, or strengthen the farmer's position within it, so more of the value flows back to the farm.

2.3 Strength in Numbers: Collective Marketing

The single most powerful remedy for the small farmer's weakness is to stop selling alone. When farmers pool their produce through a Farmer Producer Organisation (FPO) or a cooperative, many small lots become one large, attractive consignment. This aggregation transforms their position: they can negotiate better prices, sell directly to bulk buyers and processors, buy inputs cheaply in bulk, invest together in storage and grading, and reach markets no individual could access alone. India's dairy cooperative movement is the outstanding proof of this principle, having turned millions of small milk producers into a collective force that captures a fair share of the consumer's rupee. The nationwide push to form thousands of new FPOs seeks to extend this strength to crop farmers everywhere.

Farmer's Tip

Alone, you are a price-taker; together, you become a price-maker. Joining or forming an FPO is often the single most profitable decision a small farmer can make, it turns a handful of produce into a consignment worth bargaining over.

2.4 Going Digital and Direct

Technology is opening doors that were shut to farmers for generations. The electronic National Agriculture Market (e-NAM) links mandis across the country on a single online platform, so that buyers from far away can bid for a farmer's produce, creating real competition and transparent price discovery instead of a quiet deal with a local trader. Beyond e-NAM, farmers and FPOs increasingly

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sell directly to consumers, retailers, hotels, and online grocery platforms, cutting out layers of intermediaries. Farmer markets that let growers sell straight to city buyers, and mobile apps that broadcast daily prices across markets, further tilt the balance toward the farmer. Direct and digital marketing, in short, shortens the chain and arms the farmer with information.

2.5 Adding Value Before Selling

A farmer need not always sell raw produce at the raw-produce price. Even simple steps can raise the value of what leaves the farm. Cleaning, sorting, and grading produce into uniform quality lots fetches a premium, because buyers pay more for reliability. Basic processing turning tomatoes into puree, fruit into jam, milk into paneer, or grain into flour captures value that would otherwise go to a distant factory. Attractive packaging and a recognisable brand, especially for organic or regional specialty produce, can multiply the price. Value addition lets the farmer earn not just as a grower, but as a maker and it also reduces waste by using produce that might not sell well fresh.

2.6 Storing Well and Timing the Market

Prices are lowest at harvest, when everyone sells at once, and higher later, when supply thins. A farmer who can store produce safely can wait for a better price instead of selling in distress. Proper warehouses, cold storage for perishables, and scientific grain storage all make this possible. The warehouse receipt system goes a step further: a farmer can deposit produce in a certified warehouse, receive a receipt, and even borrow against it — meeting urgent cash needs without being forced to sell at the bottom of the market. Staggering sales over time, rather than dumping the whole harvest at once, helps the farmer catch better prices and steadies income through the year.

2.7 Benefits of Modern Marketing

Modern Marketing Strategy	Benefit to the Farmer
Collective selling through FPOs	Stronger bargaining power and access to bulk buyers
e-NAM and digital platforms	Wider market, transparent prices, better competition
Direct and farmer-market sales	Fewer middlemen, larger share of the final price
Grading, processing, branding	Premium prices and reduced waste through value addition

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Modern Marketing Strategy	Benefit to the Farmer
Storage and warehouse receipts	Freedom to sell later at higher prices; credit without distress sale
Market information services	Informed decisions on where and when to sell

3. Case Studies: Marketing That Paid Off

The strategies above are not theory; they have reshaped the fortunes of real farmers and regions.

3.1 The Dairy Cooperative Movement

India's dairy cooperatives are the classic success story of collective marketing. By organising millions of small milk producers, collecting milk twice a day, processing it, and marketing it under trusted brands, the cooperative model ensured that the bulk of the consumer's payment flowed back to the farmer. It turned a scattered, weak set of producers into one of the most powerful and equitable agricultural value chains in the world, and it remains the template that crop-based FPOs aim to follow.

3.2 Farmer Producer Organisations in Action

Across the country, FPOs have enabled small farmers to do together what none could do alone set up collection centres and grading units, negotiate directly with large buyers and exporters, and secure better prices for vegetables, fruits, pulses, and spices. By aggregating produce and sharing costs, member farmers have raised their incomes while also lowering their input expenses through bulk purchase.

3.3 Better Prices Through e-NAM

Farmers trading on the electronic National Agriculture Market have benefited from competitive, countrywide bidding for their produce. When buyers from other states can bid online, prices are often higher than a local ring of traders would offer, and payment reaches the farmer's bank account directly and transparently reducing both underpayment and delay.

3.4 Direct-to-Consumer Selling

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Groups of farmers running weekly farmer markets and direct-supply arrangements with urban customers and online platforms have shown how much can be gained by selling straight to the buyer. By capturing the retail margin themselves, these farmers earn substantially more for the same produce, while consumers get fresher food at fair prices a genuine win for both ends of the chain.

4. Policy Support and Government Initiatives

A range of government programmes now supports better agricultural marketing.

- **National Agriculture Market (e-NAM):** A pan-India online trading platform that links mandis, enables transparent price discovery, and gives farmers access to buyers across the country.
- **Formation and Promotion of 10,000 FPOs:** A central scheme to create and support thousands of new Farmer Producer Organisations, strengthening collective marketing by small farmers.
- **Minimum Support Price (MSP) and public procurement**: Assured prices and government purchase of key crops provide a safety net against price crashes.
- **Agriculture Infrastructure Fund:** Financing support for building storage, cold chains, grading units, and other post-harvest infrastructure.
- **Marketing reforms**: Model laws promoting direct marketing, contract farming, and private and electronic markets aim to widen farmers' selling options.
- **Warehouse receipt system and Krishi Vigyan Kendras**: Enable storage-based credit and train farmers in grading, value addition, and market planning.

5. Key Takeaways

- The farmer's biggest challenge is often marketing, not production.
- Poor prices come from small quantities, weak bargaining power, perishability, lack of information and storage, and long chains of middlemen.
- Collective marketing through FPOs and cooperatives turns price-takers into price-makers.
- Digital and direct marketing, e-NAM, e-commerce, and farmer markets — shorten the chain and reveal fair prices.
- Grading, processing, packaging, and branding add value and fetch premium prices.
- Storage and warehouse receipts let farmers avoid distress sales and sell when prices are higher.

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- Government schemes, e-NAM, the 10,000 FPO programme, MSP, and the Agriculture Infrastructure Fund support these strategies.

6. Conclusion

Growing a good crop is only half the farmer's task; selling it well is the other half, and for too long it has been the half where the farmer loses. The old pattern, small farmers selling alone, in haste, to a handful of local buyers, with no information and no choice was almost designed to keep prices low. Modern marketing rewrites that pattern. It gives farmers strength through unity, reach through technology, extra earnings through value addition, and freedom through storage.

None of these strategies requires the farmer to grow a single extra kilogram. They simply ensure that more of the value already created on the farm actually returns to it. When a farmer joins an FPO, checks prices on a phone, grades and packs the produce, sells directly or on a national platform, and stores the surplus to sell at a better time, the result is a larger and steadier income from the same harvest. Backed by supportive policies and a growing digital marketplace, Indian farmers today have more tools than ever to bridge the gap between farm and market. The journey from farm to market need no longer be one where the farmer's share shrinks at every step, it can become the journey where hard work finally earns its rightful reward.

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Combating Land Degradation through Tree-Based Farming: A Nature-Based Solution for Sustainable Agriculture

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Abstract

Land degradation is a major global challenge that threatens agricultural productivity, food security,biodiversity, and ecosystem services. Unsustainable land use practices, deforestation, soil erosion, nutrient depletion, salinization, and climate change have accelerated the deterioration of productive landscapes, particularly in developing countries. Tree-based farming, encompassing agroforestry and integrated tree–crop–livestock systems, has emerged as an effective nature-based solution to restore degraded lands while promoting sustainable agricultural production. By integrating trees with crops and/or livestock, these systems improve soil fertility, enhance carbon sequestration, reduce erosion, conserve water, increase biodiversity, and strengthen the resilience of farming systems to climate variability. In addition to ecological benefits, tree-based farming diversifies farm income through the production of timber, fruits, fodder, fuelwood, and other non-timber forest products, thereby improving rural livelihoods and reducing economic risks. This review synthesizes current evidence on the role of tree-based farming in combating land degradation, highlighting its ecological, economic, and social benefits. It also discusses major tree-based farming models, mechanisms of land restoration, policy initiatives, and successful case studies from India and across the globe. The review concludes that tree-based farming represents a sustainable and climate-resilient pathway for restoring degraded landscapes, enhancing ecosystem services, and achieving multiple Sustainable Development Goals related to land restoration, climate action, food security, and rural development.

Keywords: Land degradation, Tree-based farming, Agroforestry, Nature-based solutions, Sustainable agriculture, Soil restoration, Climate resilience, Carbon sequestration, Ecosystem services, Sustainable Development Goals (SDGs).

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Introduction

Land degradation has become one of the key environmental issues facing agriculture in the world today. Defined as the loss in the quality of the soil, decrease in its productivity, decline in biological diversity, and decrease in the amount of organic matter present, land degradation has become one of the greatest challenges to the sustainability of agriculture. As per the UN Convention to Combat Desertification (UNCCD), up to 40% of the world's land area has been degraded in some form, impacting billions of people around the globe.

The traditional approach that focused only on external input has mostly treated the symptom of land degradation and not the cause behind it. This has led to a move towards nature-based solutions that restore ecological function and agricultural production at the same time. One such nature-based solution that has attracted much attention is the use of tree-based farming systems. Tree-based farming systems combine both environmental restoration and livelihood improvement. Through the inclusion of woody perennials in agricultural ecosystems, tree-based farming has been able to contribute to soil health, carbon sequestration, conservation of biodiversity, climate regulation, and farm incomes.

Tree-Based Farming: Harnessing Nature to Restore Agricultural Landscapes

Land rehabilitation needs to adopt techniques that operate on the principles of working with nature rather than fighting it. Tree-based agriculture is one such practice since it involves the integration of trees in agricultural systems in a way that complements crop and animal production. Unlike traditional production systems that have been known to make production ecosystems less complex, tree-based farming increases resource use efficiency and ecological complexity in farming systems.

Trees act as ecological engineers in farming systems. Through their deep roots, they are able to prevent soil erosion, conserve rainfall, recycle nutrients from deeper soil layers and increase soil carbon by adding constant amounts of litter. The presence of trees in the farm creates conditions which favor crop production even when the climate may be unfavorable for growth.

Further, tree-based agriculture provides several ecosystem services while producing marketable products like timber, fruits, fodder, fuel wood, medicinal plants, bamboo, gums, and resin. It is the unique characteristics of tree-based systems that set them apart from traditional monoculture farming and thus make them well-suited to achieve ecological rehabilitation and sustainable livelihoods.

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Ecological Functions of Tree-Based Farming in Restoring Degraded Lands

Agricultural systems that integrate trees help regenerate and rejuvenate degraded soils by revitalizing the ecological functions required for agricultural production. Compared to conventional farming systems where external inputs are used extensively, tree-based farming contributes towards regenerating soil health, conserving resources, and increasing the resilience of the farm ecosystems.

The most significant advantage of incorporating trees into farming systems is the positive effects it has on soil health. Decomposing litter in the form of leaves, twigs, and fine roots from the trees contributes significantly to soil organic matter content, improves soil fertility, and provides nutrients that are available to crops through enhanced microbial activity.

Tree roots stabilize soil and improve soil and water conservation. The root systems of trees hold soil particles together and prevent erosion by wind and water action. The canopy cover of the trees reduces the force of the raindrops falling onto the soil surface. Enhanced infiltration rates and reduced runoff contribute positively to soil moisture and ground water levels.

Tree-based agriculture has another important contribution in the form of increasing biodiversity and provision of ecosystem services. Trees offer shelter to pollinating insects, birds, and other organisms that help regulate pests and aid in pollination. On the other hand, trees create ideal conditions for crop production by moderating the microclimate of farms through temperature reduction and windbreaks.

Overall, all these services increase the productivity of degraded soils while at the same time decreasing reliance on chemicals. In this way, tree-based agriculture creates an environmentally friendly approach towards agricultural production.

Economic and Livelihood Benefits of Tree-Based Farming

Apart from the ecological benefits, there is an array of economic benefits that accrue from using trees in agricultural practices. Through combining the use of trees with other agricultural produce like crops and livestock, the farming households are able to diversify their sources of income. The tree-based agricultural practice produces a wide range of agricultural produce like timber, fruits, fuel wood, fodder, bamboo, medicines, gum, and many other products from the forests.

Diversifying the sources of income also ensures that farmers become resilient to the climatic and market fluctuations. Whenever there is a failure of crop production as a result of climatic change or insect infestation, the trees continue producing income-generating products. This is very important especially for the marginal and small farmers who are easily affected by production problems.

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Tree-based agriculture is also helpful in bringing down the cost of production in the long-run. Improvement in soil fertility, recycling of nutrients, and conservation of moisture reduces the reliance on fertilizer and irrigation. In case where there are animals, the fodder trees serve as feeds for the livestock.

As the world becomes more environmentally conscious about climate change action, tree-based farming is also providing a means by which farmers can earn from carbon sequestration and payment for ecosystem services. While carbon credits are just being established in India, incentive programs in the future may be able to give financial incentives to farmers for tree cover and land management.

Tree-based farming should therefore not be perceived as an approach just to protect the environment but an investment that will yield financial gains at the same time. This is one of the ways that sustainable agriculture can be achieved through tree-based farming.

Tree-Based Farming: A Climate-Smart Solution for the Future

Climate change has made agriculture difficult by bringing about high temperatures, irregular rainfall, drought conditions, floods, and increased occurrence of weather extremities. Tree-based farming is one such climate smart agricultural approach that not only helps in combating climate change but also builds adaptability into the agricultural system.

Trees are known to be biological carbon sinks that capture carbon dioxide from the atmosphere and sequester it into the soil and vegetation form. This helps in climate change mitigation. Within a farm setting, trees help in regulating the microclimate through reduction of wind speed and creating a shade thus enabling plants and animals to cope with climatic stress. Increased soil organic carbon and infiltration rate of water into the soil make the farm resilient to drought conditions and land degradation.

There are many successful models of tree-based farming in India. Poplar-based agroforestry has helped farmers in Punjab, Haryana and western parts of Uttar Pradesh make additional money out of timber production while improving the quality of soils. Similarly, bamboo-based farming systems have reclaimed degraded lands in the North Eastern states.

Likewise, in Karnataka, coffee plantations planted under native shade trees provide biodiversity conservation along with high production, and silvopasture systems in Rajasthan and Gujarat incorporate fodder trees with livestock and provide feeds even during long dry periods.

In light of these multifaceted advantages, the Government of India has taken various measures such as National Agroforestry Policy (2014) and Sub-Mission on Agroforestry (SMAF). These are aimed at

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encouraging tree farming practices through the supply of planting materials of good quality and financial and technical assistance.

Given the increasing uncertainty associated with climate change, tree farming cannot be considered just an environmentally friendly option but a wise decision in favor of the resilience and sustainability of Indian agriculture.

Policy Support and the Way Forward

Understanding the ecological and economical advantages of tree-based agriculture, the Indian Government has undertaken various measures to promote tree-based agriculture. The National Agroforestry Policy (2014) was the first policy to integrate trees within farming systems and address concerns associated with the planting, harvesting, marketing, and value addition. Similarly, the Sub Mission on Agroforestry (SMAF) provides support to farmers in terms of provision of quality planting materials, finance and technical advice to establish tree-based farming systems.

Various research organizations, agricultural universities, ICAR, Krishi Vigyan Kendras (KVKs) and State Forest Departments have also played an important role in promoting scientific agroforestry through demonstrations, capacity building activities and location specific technology dissemination. Successful examples of poplar based agroforestry in the states of Haryana and Punjab, bamboo based farming in North-Eastern states, and coffee based agroforestry in Karnataka show how appropriate tree species can help in increasing farm incomes as well as rehabilitating degraded lands.

However, despite such efforts, tree-based agriculture is still hindered by poor awareness levels among farmers, lengthy period of gestation of trees, lack of quality planting material and marketing problems associated with tree produce. Promoting tree-based farming through community participation and climate-smart agricultural programmes will be essential for restoring degraded lands while ensuring sustainable livelihoods and environmental security.

Conclusion

Degradation of land remains one of the biggest challenges to achieving sustainable agriculture in light of climate change and increasing pressure on natural resources. Tree-based farming is one of the most promising ways of restoration of degraded lands by making a balance between productivity and preservation of the environment. By improving soil fertility, preserving water, providing biodiversity, carbon storage, and additional sources of income, tree-based farming produces many ecological and socio-economic effects at once.

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Nevertheless, there is a need for coordinated actions from all the stakeholders including policymakers, researchers, extension services, and farming community. Improvement of access to quality seedlings, better linkage to markets, raising the awareness of the farmers, and inclusion of tree-based farming into climate-smart agriculture programmes can be very important for boosting its implementation.

As India moves forward on its path of reaching the Sustainable Development Goals and Paris Agreement, tree-based farming can become a key tool for restoration of degraded lands, strengthening of the livelihoods of rural population, and creation of sustainable agricultural landscapes. Involvement in tree-based farming now can provide sustainable future with productive farms and prosperous farmers.

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Quality Seed: The First Step Towards Better Crop Production

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Abstract

Seed is the most fundamental and yet the most cost-effective input in crop production, because the returns on every other input- fertilizer, irrigation, labor, and plant protection are ultimately limited by the genetic and physiological quality of the seed that is sown. This article explains, in plain language for farmers and extension workers, what constitutes a quality seed and why it forms the true first step towards higher and more stable yields.The article describes the essential attributes of good seed: genetic purity, physical purity, germination, seedling vigor, seed health, safe moisture and uniformity, along with the formal seed-multiplication chain from nucleus seed through the breeder, foundation and certified classes, and the official tag colors that let a farmer recognize each class at a glance. Practical guidance is given on reading the seed tag, carrying out a simple home germination test, treating seed before sowing, storing seed safely and replacing seed at the recommended interval. Community seed production through the Seed Village Programme (Beej Gram Yojana) is introduced, and reliable sources of quality seed are listed. Adopting these practices can raise yields by about 15 to 20 percent at negligible additional cost, making quality seed one of the highest-return decisions available to any farmer.

Keywords: *Quality seed, seed certification, germination, seed replacement rate, seed treatment, Seed Village Program, crop productivity*

Introduction

Every good harvest begins with a single decision made long before the first rain the choice of seed. Among all the inputs a farmer invests in, such as fertilizer, water, labour and plant protection, the seed is by far the cheapest, yet it carries the greatest influence over the final yield. A field can be irrigated on time, fertilized correctly and protected from pests, but if the seed sown is weak, impure or of a poor variety, the

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returns on all those other investments are lost. This is why seed is rightly called the most critical of all farm inputs.

The seed is also the carrier of every improvement that plant breeders create. When a scientist develops a variety that resists a disease, tolerates drought or yields more grain, that advance reaches the farmer only through the seed. Sowing poor or unknown seed therefore means throwing away decades of research before the crop has even emerged. Good seed, by contrast, delivers all of that hidden value straight into the field.

Research and long field experience show that simply replacing old, poor-quality seed with good-quality seed of an improved variety can raise yields by about 15 to 20 percent, without any additional land, water or fertilizer. Very few interventions in agriculture offer such a large return for so small a cost. Understanding what makes a seed a *quality seed*, how to recognise it, and where to obtain it is therefore the true first step towards better crop production.

What Makes a Seed a "Quality Seed"?

A quality seed is not simply a seed that looks clean and plump. It is a seed that carries the genetic identity of a known, improved variety and that will establish a healthy, uniform crop in the field. Quality is judged on several attributes together, and a good seed must satisfy all of them, not just one. The main attributes are summarised below.

Quality attribute	**What it means for the farmer**
Genetic purity	The seed is true to its variety, so the whole crop behaves the same way in height, maturity, grain type and yield.
Physical purity	The lot is free from soil, chaff, straw, other crop seeds and, above all, weed seeds.
High germination	A large share of the seeds sprout, giving a full, even plant stand and avoiding gaps in the field.
Seedling vigour	Seedlings emerge quickly and grow strongly, so they compete better against weeds and stress.
Seed health	The seed is free from seed-borne diseases, insects and their eggs, which otherwise spread infection into the new crop.
Correct moisture	The seed is dried to a safe moisture level so it stores well and does not lose viability or grow mould.

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Quality attribute	What it means for the farmer
Uniformity	Seeds are even in size and free from cracks or damage, allowing smooth, accurate sowing.

Two of these attributes are often confused. Germination tells us how many seeds are alive and able to sprout, while vigour tells us how strongly and quickly those seedlings will grow, especially under less-than-ideal field conditions. A seed lot can show good germination in the laboratory yet still lack vigour, emerging slowly and unevenly in cold or crusted soil. Good-quality certified seed is selected for both.

To help farmers judge these attributes objectively, seed certification agencies test each lot against fixed minimum standards before it is sold. A few common examples of these indicative minimum standards are given below.

Crop	Min. germination (%)	Min. physical purity (%)
Wheat	85	98
Paddy (rice)	80	98
Maize	90	98
Chickpea (gram)	85	98
Mustard / rapeseed	85	97
Soybean	70	98

These figures are indicative minimum standards drawn from the Indian Minimum Seed Certification Standards; the exact values differ by crop and seed class. The key point for the farmer is simple: certified seed has already passed such a test, whereas ordinary grain kept for sowing has not.

The Hidden Cost of Poor-Quality Seed

The damage done by poor seed is easy to overlook because it rarely announces itself as a single, dramatic loss. Instead, it works quietly, and by the time the effects are visible in the standing crop, it is usually too late to correct them. Recognizing these hidden costs helps a farmer understand why quality seed is worth insisting upon.

- **Gaps and thin stands**: low germination leaves bare patches in the field, which reduce the plant population and invite weeds into the empty spaces.

- **Weed and disease introduction**: impure seed lots carry weed seeds and seed-borne pathogens directly into a clean field, creating problems that may persist for years.
- **Uneven crops:** a mixture of varieties matures at different times, making irrigation, spraying and harvesting difficult and lowering the market grade of the produce.
- **Wasted inputs**: fertilizer, water and labour spent on a weak crop cannot be recovered, so poor seed multiplies every other cost on the farm.
- **Costly re-sowing:** when a stand fails badly, the farmer must buy seed again and sow late, losing both money and the best part of the season.

The Seed Chain: From the Breeder to the Farmer

Good seed does not appear on its own. It is produced through a carefully controlled chain, where each generation is multiplied under supervision so that genetic purity is preserved from the plant breeder right down to the farmer's field. Each class in this chain carries a tag of a fixed color, which allows anyone to recognize at a glance what stage of seed they are handling. Knowing these classes and their tag colors is one of the most useful pieces of practical knowledge a farmer can have.

Seed class	What it is	Official tag colour
Nucleus seed	The original, genetically pure seed produced and kept by the plant breeder.	(kept by breeder; not sold)
Breeder seed	Direct progeny of the nucleus seed, produced under the breeder's supervision.	**Golden yellow**
Foundation seed	Progeny of breeder seed, multiplied by recognised agencies under certification.	**White**
Certified seed	Progeny of foundation seed; this is the seed the farmer buys and sows.	**Azure blue**
Truthfully labelled seed	Seed sold after testing only germination and physical purity, without full field certification.	**Opal green**

For everyday sowing, the farmer will most often be buying **certified seed** (blue tag) or truthfully labeled seed (opal green tag). Both are legitimate and legal under the Seeds Act, 1966. The difference is that certified seed has passed full field inspection and laboratory testing, giving the highest assurance of genetic purity, while truthfully labeled seed is tested only in the laboratory, and its quality is guaranteed by the producer. When available and affordable, certified seed is the safer choice for the main crop.

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Reading the Seed Tag: A Farmer's Checklist

The seed tag stitched to every genuine bag is a legal document, not a decoration. Before buying, a farmer should read it carefully rather than judging seed only by how it looks. A genuine tag will show the following information, and every item should be checked.

- **Name of the crop, variety and lot number -** so the whole batch can be traced if a problem arises.
- **Germination percentage -** this is the most important figure; do not accept seed with a low or missing germination value.
- **Physical (genetic) purity percentage -** higher purity means fewer weed and other-crop seeds.
- **Date of test and the "valid until" date -** seed loses its ability to germinate over time, so never buy seed that is past this date.
- **Name of the producing agency -** a genuine bag carries the name and seal of a recognized producer or certification agency.

Quick rule at the shop

- Match the tag color to the seed class you are paying for - blue for certified, opal green for truthfully labeled.
- Always read the germination percentage and the validity date before paying.
- Insist on a printed cash memo or bill that records the crop, variety and lot number.
- Buy only from licensed dealers, government outlets or recognized agencies.

A Simple Germination Test You Can Do at Home

A farmer does not need a laboratory to check whether seed is worth sowing. A simple test done a week or two before sowing can prevent the costly mistake of planting dead or weak seed, and it takes only a handful of seeds and a piece of cloth.

- Count out 100 seeds at random from the lot to be sown.
- Spread them on a wet cloth or several layers of moist newspaper, cover with another moist layer, and roll it loosely.
- Keep the roll in a warm, shaded place and sprinkle water daily so it stays moist but not soaked.

- After the normal germination period for that crop, count how many seeds have sprouted into healthy seedlings.

The number that sprout out of 100 is the germination percentage. If, for example, 90 seeds germinate, germination is 90 percent, which is excellent. If only 60 germinate, the farmer knows to increase the seed rate accordingly, or better still, to obtain fresh seed. A simple habit of testing before sowing removes almost all the risk of a failed stand.

Saved Seed, Certified Seed and Seed Replacement

Many farmers save a part of their harvest to sow the following season. For self-pollinated crops such as wheat, paddy and pulses, saving seed for a year or two is acceptable, provided the seed was of good quality to begin with and has been cleaned, dried and stored properly. However, seed saved again and again gradually loses its purity and vigor. Weed seeds creep in, diseases build up, and the variety slowly deteriorates, so yields fall year after year without the farmer noticing a single dramatic cause.

This is why agricultural scientists recommend regular **seed replacement**. The share of the total cropped area sown with fresh, good-quality seed each season, instead of old farm-saved seed, is called the **Seed Replacement Rate (SRR)**. A higher seed replacement rate is strongly linked to higher and more stable yields. For hybrid crops the position is stricter still: hybrid seed *must* be purchased fresh every season, because seed saved from a hybrid crop will not breed true and will give a poor, uneven stand in the next year.

As a practical guideline, farmers should replace the seed of self-pollinated crops with certified seed at least once every three to four years, and buy fresh hybrid seed every single season. Studies on crops such as chickpea and pigeonpea have shown clear yield gains when farmers move from old farm-saved seed to good-quality replacement seed, confirming that this simple change pays for itself.

Treat the Seed Before You Sow

Even good-quality seed benefits from treatment before sowing. Seed treatment is a low-cost step that protects the emerging seedling from seed-borne and soil-borne diseases and from early insect attack, giving the crop a strong, clean start. It is one of the highest-return practices in all of crop production relative to its cost. The order of treatment matters, as shown below.

Order	Type of treatment	Common example	Purpose
1	**Fungicide**	Thiram or Carbendazim @ 2–3 g per kg seed	Controls seed-borne and soil-borne fungal diseases.

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Order	Type of treatment	Common example	Purpose
2	**Bio-agent**	Trichoderma viride @ 4–6 g per kg seed	Protects against root rot, wilt and damping-off.
3	**Insecticide**	Recommended seed-treatment insecticide	Guards against early sucking pests, termites and shoot fly.
4	**Biofertilizer**	Rhizobium / Azotobacter / PSB culture	Boosts nodulation and nutrient uptake, especially in pulses.

Always follow the dose printed on the product label and the recommendation in your local package of practices. Do not mix a biofertilizer culture directly with a chemical fungicide in the same coat, and apply the culture last, just before sowing.

Storing Seed Safely on the Farm

Where a farmer does save seed, careful storage decides whether that seed is worth sowing next season. Seed is a living material that continues to breathe, and warmth and moisture are its two greatest enemies. Poorly stored seed loses germination silently, so that a farmer may sow a full bag only to find half the field bare.

- Dry the seed thoroughly in the sun before storage, then let it cool in the shade before bagging.
- Store in clean, dry, airtight containers or bags, kept off the floor on a wooden platform or bricks.
- Keep the store cool, dry and well ventilated, and protect it from rats, insects and dampness.
- Label every container with the crop, variety and year, and always sow the oldest good seed first.

Growing Your Own Quality Seed: The Seed Village Concept

Because farm-saved seed still accounts for the large majority of the seed sown in India, improving its quality at the village level can lift the productivity of whole regions. This is the idea behind the seed village, in which a trained group of farmers in one compact area produces good-quality seed of a chosen variety, both for their own use and to meet the local demand of neighboring farms.

The Government of India supports this approach through the **Seed Village Programme (Beej Gram Yojana)**, running since 2014–15 as a component of the Sub-Mission on Seeds and Planting Materials. Under the programme, financial assistance is provided for the distribution of foundation or certified seed at 50 percent of the seed cost for cereal crops and 60 percent for pulses, oilseeds, fodder and green-manure crops — for up to one acre per farmer. Assistance is also given for seed-storage bins so that

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farmers can preserve their produced seed safely until the next sowing season, and for training farmers in seed production and seed technology.

Where to Obtain Quality Seed

Reliable, good-quality seed is available from several trusted sources, and buying from these outlets is the best protection against spurious or mislabelled seed sold in the open market. Farmers should prefer:

- the National Seeds Corporation and State Farms Corporation of India;
- State Seed Corporations and State Departments of Agriculture;
- State Agricultural Universities and their research stations, and Krishi Vigyan Kendras (KVKs);
- licensed private seed dealers and recognized, reputable seed companies.

Do's and Don'ts at the time of purchase

- DO buy seed well before the sowing season, so good varieties are still in stock.
- DO keep the tag, bill and empty bag until the crop is well established, in case of a complaint.
- DON'T buy loose, untagged seed or seed sold at unusually cheap prices.
- DON'T judge seed by appearance alone — always read the tag and the germination value.

Quality Seed Pays: A Simple Economics

The cost of good seed is small compared with the total cost of raising a crop, yet its effect on income is large. Certified seed usually costs only a little more than the grain a farmer might otherwise sow, and government schemes further reduce that cost through subsidy. Against this modest extra outlay stands a yield gain of roughly 15 to 20 percent, together with fewer gaps, fewer weeds and a more uniform, better-grade produce that fetches a higher price. On almost any farm, quality seed returns several rupees for every extra rupee spent on it, which is why it is regarded as the single most cost-effective decision in the whole cropping calendar.

Conclusion

The seed is the smallest and cheapest input a farmer buys, yet it sets the ceiling on everything the crop can become. No amount of fertilizer, water or care can lift a crop beyond the potential locked inside the seed at sowing. By choosing certified or truthfully labelled seed of an improved variety, reading the tag before buying, testing germination, treating the seed before sowing, storing saved seed with care, and

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replacing seed regularly, a farmer can secure a healthier, more uniform and higher-yielding crop at very little extra cost.

Extension workers have a decisive part to play in turning this knowledge into practice — by guiding farmers to trusted seed sources, helping them read seed tags, promoting seed treatment and seed replacement, and supporting community seed production through programmes such as Beej Gram Yojana. Quality seed is, in the truest sense, the first step towards better crop production. Get this first step right, and every other effort in the field is rewarded many times over.

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Soil Salinity and Waterlogging Management in Irrigated Areas

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Abstract

Soil salinity and waterlogging are among the most serious threats to agricultural productivity in irrigated regions, reducing crop yields, degrading soil health, and affecting farmers' livelihoods. These problems arise due to excessive irrigation, poor drainage, high evaporation, and the accumulation of soluble salts in the root zone. If left unmanaged, they can lead to declining land productivity, inefficient water use, and environmental degradation. This article explains the causes, impacts, and practical management strategies for controlling salinity and waterlogging in irrigated agriculture. It highlights the importance of efficient irrigation methods, proper drainage systems, land leveling, crop rotation, salt-tolerant crop varieties, gypsum application, and integrated soil and water management practices. The role of modern technologies such as remote sensing, precision irrigation, and soil moisture monitoring is also discussed. By adopting sustainable management practices, farmers can restore soil productivity, conserve water resources, improve crop performance, and ensure long-term agricultural sustainability and food security in irrigated farming systems.

Keywords: Soil salinity, Waterlogging, Irrigation management, Drainage, Salt-tolerant crops, Precision irrigation, Soil health, Sustainable agriculture, Water conservation, Food security.

Introduction

Drive through the canal command areas of Haryana, western Uttar Pradesh, or parts of Punjab in the peak of summer, and amid the lush green wheat and paddy fields, you will occasionally spot patches of land that look as if they have been dusted with snow. These white, crusted patches are not a natural quirk of the landscape; they are the visible scars of one of Indian agriculture's most persistent and under-discussed problems: soil salinity and waterlogging in irrigated areas.

For decades, assured irrigation has been celebrated as the backbone of India's food security, powering the Green Revolution and turning water-scarce regions into grain bowls. Yet this very success carries a hidden cost. Wherever water is applied generously but drained poorly, salts accumulate, water tables rise, and once-productive soils slowly slip into decline. The Indian Council of Agricultural Research and the Central Soil Salinity Research Institute (CSSRI) estimate that several million hectares of irrigated land across India are affected by varying degrees of salinity, sodicity, and waterlogging a quiet erosion of the very foundation that feeds the nation.

This article looks beneath the surface of this problem: why it happens, how it manifests, what science and traditional wisdom together offer as solutions, and what a young soil scientist believes should guide the way forward.

Understanding the Twin Problem: Salinity and Waterlogging

Soil salinity and waterlogging are two sides of the same coin, and in irrigated agriculture, they frequently travel together. Waterlogging occurs when the water table rises close to the root zone, saturating the soil and depriving roots of oxygen. Salinity develops when soluble salts, chlorides, sulfates, and carbonates of sodium, calcium, and magnesium accumulate in the root zone faster than they can be leached away.

In canal-irrigated tracts, both problems typically originate from the same source: seepage from unlined canals and distributaries, combined with excessive and inefficient field irrigation. Water percolates downward, raises the water table, and as it approaches the surface, capillary action draws it upward again. On its way up, this water carries dissolved salts. When it evaporates at or near the surface, especially under the intense heat of the Indo-Gangetic plains, the water disappears into the atmosphere, but the salts remain, concentrating year after year until crop growth becomes impossible.

Sodicity, a related but distinct problem, occurs when sodium ions dominate the soil's exchange complex, causing clay particles to disperse. This destroys soil structure, collapses pore spaces, and

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creates the hard, impermeable, alkaline soils locally known as 'usar' or 'reh' land across the Gangetic plains, some of the most difficult soils to reclaim in the country.

How Widespread is the Problem?

Salt-affected soils in India are estimated to extend across roughly 6.73 million hectares, spread across states including Uttar Pradesh, Punjab, Haryana, Gujarat, Rajasthan, Maharashtra, and West Bengal, based on figures compiled by CSSRI and the National Bureau of Soil Survey and Land Use Planning. A significant share of this area lies within canal command areas, precisely the tracts that were meant to be India's most productive.

Uttar Pradesh alone accounts for a substantial portion of the country's sodic (usar) lands, concentrated in districts along the middle Ganga plains where heavy clay soils, flat topography, and intensive canal irrigation combine to create ideal conditions for salt accumulation. Waterlogging compounds the problem in areas served by the Sharda Sahayak and other canal systems, where seepage losses from unlined channels are estimated to be considerable.

Table 1. Classification of Salt-Affected Soils Based on Key Diagnostic Parameters

Soil Type	ECe (dS/m)	ESP (%)	pH (Saturation Paste)	Typical Field Symptom
Saline Soil	> 4	< 15	< 8.5	White salt crust; stunted, patchy crop growth
Sodic Soil	< 4	> 15	> 8.5	Black alkaline patches; poor infiltration, hard-setting surface
Saline-Sodic Soil	> 4	> 15	Variable, often < 8.5	Combination of crusting and structural collapse
Waterlogged Soil	Variable	Variable	Variable	Water table within 1–1.5 m of surface; root asphyxiation

The Cost to Crops and Farmers

The agronomic consequences of salinity and waterlogging are severe and cascading. High salt concentrations create osmotic stress, making it physiologically difficult for plant roots to absorb water

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even when the soil appears moist, a phenomenon often called 'physiological drought.' Specific ions such as sodium and chloride can also become directly toxic to plant tissues at elevated concentrations, disrupting enzyme activity and photosynthesis.

Waterlogging, meanwhile, starves roots of oxygen, halts nutrient uptake, and favors the proliferation of anaerobic soil pathogens. Crops such as wheat, sensitive to both stresses, may show yield reductions ranging from 20 to 80 percent depending on the severity and duration of exposure. Paddy is comparatively more tolerant of waterlogging but still suffers under high sodicity, particularly during the seedling stage.

Diagnosis: Reading the Signs Early

Effective management begins with early and accurate diagnosis. Farmers and extension workers can watch for several field-level indicators even before formal soil testing: white crusts after irrigation or rainfall (indicating salinity), dark greasy patches with poor water infiltration (indicating sodicity), stunted and patchy crop stands, and standing water or a persistently moist subsoil layer close to the surface (indicating a high-water table).

Formal diagnosis relies on measuring electrical conductivity of the saturation extract (ECe), exchangeable sodium percentage (ESP), soil pH, and water table depth through piezometers or observation wells. The Krishi Vigyan Kendra (KVK) network and State Agriculture Departments in India have increasingly integrated these diagnostics into their soil health card programs, allowing farmers to receive periodic assessments alongside fertilizer recommendations.

Management Strategies: A Layered Approach

No single intervention reclaims salt-affected or waterlogged land. Decades of research at CSSRI, Karnal, and its regional stations, along with State Agricultural Universities, have converged on an integrated approach combining engineering, chemical, and biological measures.

1. Drainage: Lowering the Water Table: Subsurface drainage, using perforated pipes laid at calculated depths and spacing, remains the most reliable engineering solution for waterlogged and saline soils. By intercepting and removing excess groundwater along with dissolved salts, subsurface drainage systems have demonstrated the ability to reclaim severely degraded land within two to three

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cropping seasons in areas such as the Haryana canal command, where CSSRI-led demonstration projects have shown substantial yield recovery.

2. Chemical Reclamation: Gypsum and Leaching: For sodic soils, the application of gypsum (calcium sulphate) remains the gold standard. Gypsum supplies calcium ions that displace sodium from the soil exchange complex; the displaced sodium is then leached out of the root zone with adequate irrigation water. The gypsum requirement is calculated based on the soil's ESP and desired depth of reclamation, and is typically applied at rates ranging from 5 to 15 tonnes per hectare for moderately to severely sodic soils, often in split doses over multiple seasons.

3. Agronomic and Crop-Based Management: While reclamation proceeds, farmers need not abandon cultivation altogether. Salt-tolerant crop varieties such as CSSRI's CSR series of rice varieties bred specifically for sodic and saline conditions allow productive use of moderately affected land during the reclamation period. Dhaincha (Sesbania) is widely used as a green manure crop on newly reclaimed sodic soils; it tolerates high pH, adds organic matter, and improves soil structure as it decomposes.

Raised-bed planting, laser land leveling, and adoption of the System of Rice Intensification (SRI) also help manage water more precisely, reducing both waterlogging risk and unnecessary salt mobilization. Laser leveling in particular has shown water-saving benefits of 20 to 30 percent in several field trials across Punjab and Haryana, directly reducing the seepage that drives salinization.

4. Biological Drainage and Agroforestry: An elegant and increasingly popular approach is biodrainage: the strategic planting of deep-rooted, fast-transpiring tree species such as Eucalyptus, Populus (poplar), and Prosopis juliflora along field boundaries and canal banks in waterlogged tracts. These trees act as biological pumps, drawing down the water table through transpiration and reducing seepage-driven salinity, while also generating timber income for farmers.

Policy Support and Institutional Framework

Recognizing the scale of the problem, the Government of India and several state governments have integrated salinity and waterlogging management into major schemes. The Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), through its 'Per Drop More Crop' component, promotes micro-irrigation to reduce over-application of water — directly addressing one of the root causes of secondary

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salinization. The Rashtriya Krishi Vikas Yojana (RKVY) has supported state-specific reclamation projects, including gypsum application subsidies and community drainage infrastructure.

In Uttar Pradesh, the Usar Land Reclamation Programme, implemented in partnership with the World Bank in earlier decades and continued through state initiatives, has reclaimed substantial areas of sodic land through a combination of gypsum application, community drainage, and farmer training delivered through the ATMA (Agricultural Technology Management Agency) framework and local KVKs. These institutional convergence models, where technical research from CSSRI meets extension delivery through ATMA-KVK networks, offer a template worth strengthening further.

A Case in Point: Farmer-Led Reclamation in Western Uttar Pradesh

Farmer groups in several sodic-affected blocks of western Uttar Pradesh have demonstrated that reclamation, though slow, is achievable at the community level when technical guidance and modest subsidies are available. Working through KVK-facilitated farmer groups, clusters of smallholders have pooled resources for gypsum application and shared subsurface drainage outlets, converting unproductive usar patches into land capable of supporting sodicity-tolerant paddy varieties within three to four years.

Such examples underline an important lesson for extension practice: reclamation technologies exist and are well-proven, but adoption depends heavily on farmer organization, access to affordable gypsum, and sustained field-level handholding precisely the role that a strong extension system is meant to play.

Traditional Wisdom Meets Modern Science

Long before soil testing laboratories existed, farming communities in salt-affected tracts of the Gangetic plains had already developed empirical strategies for coping with usar land. Practices such as leaving affected patches fallow during the monsoon to allow natural leaching, growing salt-tolerant grasses like Karnal grass (Diplachne fusca) as fodder on marginal sodic patches, and rotating dhaincha green manuring with cereal crops all predate formal reclamation science by generations.

Modern research has, in many cases, validated and refined this traditional knowledge rather than replaced it. CSSRI's own reclamation package for usar lands, involving dhaincha green manuring,

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gypsum application, and rice-wheat rotation, closely mirrors practices that progressive farmers in Uttar Pradesh and Haryana had arrived at independently through generations of trial and observation. This convergence is a useful reminder for extension professionals: effective technology transfer often works best when it builds upon, rather than dismisses, indigenous farmer knowledge.

The Extension Challenge: From Laboratory to Field

Perhaps the most persistent gap in salinity and waterlogging management in India is not scientific but organizational. Reclamation technologies, gypsum dosing, subsurface drainage design, biodrainage plantation, and salt-tolerant variety selection are well documented in research station trials. Yet uptake at the farm level remains uneven, particularly among smallholders who cannot easily afford upfront gypsum costs or navigate the technical calculations involved in determining application rates.

This is precisely where a well-functioning extension system earns its relevance. The ATMA framework, with its emphasis on farmer interest groups and bottom-up planning, is well suited to organizing collective reclamation efforts, pooling gypsum purchases, sharing drainage outlets, and coordinating group leaching schedules that are far more effective than isolated individual efforts on fragmented landholdings. KVK scientists, through method demonstrations and front-line demonstrations (FLDs) on farmers' fields, have played a documented role in building farmer confidence in reclamation technologies that might otherwise seem risky or unfamiliar.

Digital tools are beginning to supplement this human extension infrastructure. Mobile-based soil health advisories, GIS-based mapping of salinity-prone zones by state remote sensing agencies, and SMS-based irrigation scheduling alerts are gradually making it easier to identify vulnerable areas before they deteriorate further, and to reach farmers with timely, location-specific advice rather than generic recommendations.

A Simplified Decision Pathway for Farmers

Extension workers advising farmers on suspected salt-affected or waterlogged land can follow a broadly sequential diagnostic and action pathway, summarized below.

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STEP 1: Observe field symptoms — white crust, dark patches, stunted growth, or standing water
↓
STEP 2: Get soil tested (ECe, ESP, pH) and check water table depth via nearby well/piezometer
↓
STEP 3: Classify — Saline / Sodic / Saline-Sodic / Waterlogged (see Table 1)
↓
STEP 4: Select intervention — Gypsum + leaching (sodic) | Leaching + drainage (saline) | Subsurface drainage + biodrainage (waterlogged)
↓
STEP 5: Grow tolerant varieties and green manure crops (e.g., dhaincha) during the reclamation period
↓
STEP 6: Monitor soil parameters annually and adjust irrigation scheduling to prevent recurrence

The Road Ahead

As climate variability intensifies and groundwater quality in many parts of the Indo-Gangetic plains continues to deteriorate with rising incidence of high residual sodium carbonate (RSC) in tubewell water the salinity and waterlogging challenge is unlikely to disappear on its own. If anything, the pressure on irrigated soils is likely to growThe way forward lies in treating salinity and waterlogging not as isolated soil problems but as symptoms of a broader water management challenge. Canal lining to reduce seepage, conjunctive use of canal and groundwater, precision land leveling, promotion of biodrainage plantations, and continued farmer access to soil testing and gypsum subsidies together form a realistic, evidence-based pathway.

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Biochar: An Emerging Soil Amendment for Indian Conditions

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Abstract

Crop residue burning across the Indo-Gangetic plains destroys valuable organic carbon while contributing heavily to regional air pollution, even as Indian soils face a long-term decline in soil organic matter. Biochar, a stable, carbon-rich material produced by pyrolyzing crop residues and other biomass under low-oxygen conditions, offers a potential answer to both problems simultaneously. This article reviews the science underlying biochar's soil benefits, synthesizes evidence from Indian field trials across acidic, sandy, and saline-affected soils, and examines its particular relevance to residue management in Punjab and Haryana. It further discusses practical considerations for farmers, including application rates, feedstock quality, and cost-benefit dynamics, along with emerging opportunities in climate-smart agriculture and carbon markets. While biochar is not a universal solution and its benefits accrue gradually rather than immediately, the evidence suggests it holds genuine promise as a locally producible amendment capable of improving soil organic carbon, water retention, and long-term soil health under Indian conditions, provided adoption is supported by demonstration-based extension and accessible, small-scale production technology.

Introduction

Every rabi and kharif harvest season, plumes of smoke rise across the fields of Punjab, Haryana, and western Uttar Pradesh as farmers burn crop residues to quickly clear their land for the next sowing. This practice, though agronomically convenient, releases valuable carbon and nutrients into the atmosphere, contributes heavily to regional air pollution, and destroys the very organic matter that

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could have nourished the soil. What if that same crop residue, instead of going up in smoke, could be transformed into a stable, carbon-rich material capable of improving soil health for decades? This is precisely the promise of biochar.

Biochar is not a new invention. Amazonian communities created remarkably fertile 'terra preta' (dark earth) soils thousands of years ago by incorporating charred organic material into otherwise poor tropical soils, patches that remain fertile today, long after the practice ceased. Modern soil science has now rediscovered and refined this ancient technique, positioning biochar as one of the more promising tools for addressing India's residue-burning crisis, declining soil organic carbon, and the need for climate-resilient agriculture.

This article examines what biochar is, how it works in the specific context of Indian soils and cropping systems, the evidence so far, and the practical challenges that stand between promising research and widespread farmer adoption.

What Exactly is Biochar?

Biochar is a carbon-rich solid produced by heating biomass, crop residues, wood waste, poultry litter, or other organic materials in a low-oxygen environment through a process called pyrolysis. Unlike ordinary burning, which combusts organic matter fully in the presence of oxygen and releases most of its carbon as carbon dioxide, pyrolysis restricts oxygen supply, converting a large share of the biomass carbon into a stable, charcoal-like solid rather than releasing it into the atmosphere.

The temperature at which pyrolysis occurs strongly influences the properties of the resulting biochar. Lower temperature pyrolysis, in the range of 350 to 500 degrees Celsius, tends to retain more volatile compounds and nutrients, producing biochar better suited for nutrient retention. Higher temperature pyrolysis, above 500 degrees Celsius, produces biochar with a more stable, highly aromatic carbon structure, greater surface area, and higher resistance to microbial decomposition, properties valued for long-term carbon sequestration and soil structural improvement.

In India, feedstocks of particular relevance include rice straw and rice husk, wheat straw, sugarcane trash, cotton stalks, and various agro-industrial residues such as groundnut shells — all abundantly available, often burned or underutilized, and well suited to conversion into biochar through appropriately scaled pyrolysis units.

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Why Biochar Works: The Underlying Soil Science

Biochar's beneficial effects on soil stem from a combination of physical, chemical, and biological mechanisms. Physically, biochar particles are highly porous, with internal surface areas that can range from tens to several hundred square meters per gram. This porous structure improves soil aeration and water-holding capacity, particularly valuable in the sandy and loamy soils common across much of semi-arid and arid India, where water retention is often a limiting factor for crop growth.

Chemically, biochar typically carries a high cation exchange capacity (CEC) and, depending on feedstock and pyrolysis conditions, may be alkaline in reaction, a property that makes it particularly useful as an amendment for acidic soils common in parts of eastern and northeastern India, where biochar application has been shown to raise soil pH and reduce aluminum toxicity that otherwise constrains root growth.

Biologically, the porous structure of biochar provides habitat and refuge for beneficial soil microorganisms, including mycorrhizal fungi and nitrogen-fixing bacteria, protecting them from predation and desiccation. Several studies have documented enhanced microbial biomass and activity in biochar-amended soils, contributing to improved nutrient cycling over time.

The Indian Evidence Base

Research institutions across India, including the Indian Agricultural Research Institute (IARI), Punjab Agricultural University (PAU), and several State Agricultural Universities, have conducted field trials examining biochar's performance under Indian cropping conditions. Findings, while still accumulating, are broadly encouraging for specific soil types and cropping systems.

Table 1. Reported Effects of Biochar Application Across Indian Field Trials

Soil / Region Context	Biochar Feedstock	Application Rate	Reported Effect
Acidic soils, eastern India	Rice husk	5–10 t/ha	Raised soil pH; reduced Al toxicity; improved rice yield
Sandy loam, semi-arid Punjab	Wheat straw	5 t/ha	Improved water-holding capacity; reduced irrigation frequency

Soil / Region Context	Biochar Feedstock	Application Rate	Reported Effect
Degraded/marginal soils	Mixed crop residue	10 t/ha	Increased soil organic carbon and microbial biomass
Saline-affected soils	Rice straw	5–8 t/ha	Modest reduction in soil ECe; improved seedling establishment

Biochar and the Crop Residue Burning Problem

Perhaps biochar's most compelling case in the Indian context lies in its potential to address crop residue burning, an entrenched practice that contributes substantially to seasonal air quality crises across the Indo-Gangetic plains, particularly in Punjab and Haryana following paddy harvest. Estimates from state pollution control boards and agricultural departments suggest that tens of millions of tonnes of paddy straw are burned annually across these two states alone.

Converting even a modest share of this residue into biochar through decentralized, village or cluster-level pyrolysis units offers a dual benefit: it diverts residue away from open burning, reducing particulate emissions, while generating a value-added soil amendment that farmers can either apply on their own fields or sell as an additional income stream. Several pilot projects, including initiatives supported by state agricultural departments and private agritech start-ups, have begun testing small-scale, mobile pyrolysis units designed to operate directly at the field edge or at village collection points, reducing the logistical burden of transporting bulky residue.

Practical Considerations for Farmers

For farmers and extension workers considering biochar, several practical factors influence its effectiveness and economic viability.

1. Application Rate and Method

Recommended application rates in Indian trials typically range from 5 to 10 tonnes per hectare, though this varies considerably with soil type, feedstock, and crop. Biochar is generally most effective

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when incorporated into the topsoil (0–15 cm) rather than surface-applied, and is often combined with farmyard manure or compost, a practice sometimes referred to as 'co-composting ', which helps offset biochar's tendency to temporarily immobilize nitrogen if applied alone in large quantities.

It is worth noting that biochar's benefits are not always immediate. Unlike a fertilizer application, which produces visible results within one growing season, biochar's improvements to soil structure, water retention, and microbial activity often become more pronounced over two to three cropping cycles, as the material integrates fully into the soil matrix.

2. Feedstock Selection and Quality Control

Not all biochar is created equal. Feedstock source and pyrolysis temperature significantly affect the final product's nutrient content, pH, and carbon stability. Biochar produced from poultry litter, for instance, tends to be nutrient-rich but less carbon-stable, while biochar from woody biomass or rice husk tends to be more stable but nutrient-poor. Farmers and extension agents should be cautious of biochar produced through poorly controlled, low-temperature smoldering, which can retain harmful polycyclic aromatic hydrocarbons (PAHs) and offer fewer benefits than properly pyrolyzed material.

Simple field-level quality indicators include a distinctly light weight relative to volume, a metallic ring when tapped, and minimal residual smoke odor, though laboratory testing for pH, ash content, and carbon stability remains the more reliable route for large-scale or commercial application.

3. Economics and Cost-Benefit Considerations

The upfront cost of biochar, whether purchased commercially or produced through on-farm pyrolysis units, remains a genuine barrier for smallholders. Commercial biochar in India is currently priced in a range that, without subsidy support, can make large-scale application economically challenging for a single small farm relative to conventional inputs like urea or DAP.

Cooperative or cluster-based production models, where a group of farmers or a Farmer Producer Organization (FPO) collectively invests in a shared pyrolysis unit and processes pooled residue, have shown more promising economics, spreading capital costs across a larger production volume while also creating a modest secondary income stream from surplus biochar sales.

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Biochar and Climate-Smart Agriculture

Beyond its direct soil benefits, biochar carries a distinctive climate dimension that has attracted growing policy interest. Because pyrolysis converts biomass carbon into a chemically stable form resistant to microbial breakdown, biochar effectively locks carbon into the soil for periods estimated to range from decades to centuries, rather than the few years typical of undecomposed crop residue. This makes biochar production and application a recognized carbon sequestration strategy, increasingly discussed within India's climate-smart agriculture and voluntary carbon market frameworks.

A small but growing number of Indian agritech and carbon-credit platforms have begun piloting biochar-linked carbon credit schemes, in which farmers or farmer collectives are compensated for verified biochar application, potentially offering an additional revenue stream that could help offset the upfront cost barrier discussed above. While still nascent and requiring careful measurement and verification protocols, this intersection of soil science and climate finance represents a promising direction for future extension and policy engagement.

How Does Biochar Compare with Other Soil Amendments?

Farmers and extension workers often ask how biochar stacks up against more familiar soil amendments such as farmyard manure (FYM), vermicompost, and gypsum. The honest answer is that biochar is not a direct substitute for any of these but rather a complementary material with a distinct role, best understood through its persistence in soil rather than its nutrient content alone.

Farmyard manure and vermicompost decompose relatively quickly, releasing nutrients within one or two cropping seasons but contributing comparatively little to long-term, stable soil organic carbon. Biochar, by contrast, supplies few readily available nutrients on its own but persists in the soil for decades, providing structural and microbial habitat benefits long after a single application. Gypsum addresses a narrower, chemistry-specific problem, sodium displacement in sodic soils, which biochar does not directly replicate, though biochar's own effect on cation exchange capacity can complement gypsum-based reclamation programs on marginal land.

Case Example: Farmer Producer Organizations and Cluster-Level Pyrolysis

A useful illustration of how biochar production might scale sustainably in the Indian context comes from cluster-level models piloted by Farmer Producer Organizations (FPOs) in parts of Punjab

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and Haryana in partnership with agricultural universities and agritech collaborators. Under these arrangements, member farmers deliver surplus paddy or wheat straw to a shared collection point equipped with a medium-scale pyrolysis unit, rather than burning residue individually in their own fields.

The resulting biochar is partly returned to contributing farmers for field application and partly sold commercially or blended into compost products for sale, generating a modest revenue stream that helps offset collection and processing costs. Early assessments of such pilot models suggest that the approach is most viable where residue volumes are sufficiently concentrated, transport distances are short, and a committed local institution, whether an FPO, KVK, or private aggregator, is available to coordinate logistics. Where these conditions are absent, individual on-farm biochar production using low-cost kiln designs remains a more realistic entry point, albeit at a smaller scale.

A Simplified Adoption Pathway

For extension workers introducing biochar to farmer groups, a phased approach tends to work better than large-scale immediate adoption, allowing farmers to build confidence through direct observation.

STEP 1: Identify locally available residue feedstock (rice straw, wheat straw, husk, stalks)

↓

STEP 2: Conduct small-scale demonstration using low-cost kiln or pit pyrolysis method

↓

STEP 3: Test biochar quality (weight, ash content, pH) before field application

↓

STEP 4: Co-compost biochar with farmyard manure to offset nitrogen immobilization

↓

STEP 5: Apply on a small demonstration plot at 5 t/ha; compare against untreated control

↓

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STEP 6: Monitor soil organic carbon, water retention, and yield over 2–3 seasons before scaling up

Institutional and Policy Landscape

Government support for biochar in India remains at an early but developing stage. The Indian Council of Agricultural Research (ICAR) has funded biochar-related research across several of its institutes, and biochar production is being explored as a complementary intervention under crop residue management schemes that primarily promote in-situ residue incorporation using machinery such as Happy Seeders. State-level agricultural departments in Punjab and Haryana have shown interest in decentralized pyrolysis as a supplementary strategy alongside existing residue management subsidies.

The Road Ahead

Biochar is not a silver bullet for Indian agriculture's soil health and residue management challenges, and it is important that its promotion avoid the overstated claims that sometimes accompany emerging soil amendments. Its benefits are real but soil-specific, feedstock-dependent, and realized gradually rather than immediately. Nonetheless, few other interventions offer such a direct convergence of benefits: improved soil organic carbon, better water retention, reduced dependence on chemical inputs over time, decreased residue burning, and long-term carbon sequestration from a single, locally producible material.

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Soil Health Cards and Nutrient Management Based on Testing

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Abstract

Soil is the living foundation of agriculture, yet years of imbalanced and excessive fertilizer use have degraded its fertility across large parts of India. The Soil Health Card (SHC) Scheme, launched by the Government of India in 2015, seeks to reverse this trend by giving every farmer a field-specific report of soil nutrient status together with crop-wise fertilizer recommendations. This article explains what a Soil Health Card is, why testing the soil before fertilizing is essential, and how the twelve parameters it measures translate into practical field decisions. It describes the shift from blanket fertilizer doses to soil-test-based and balanced nutrient management, drawing on established scientific approaches such as Soil Test Crop Response (STCR), Integrated Plant Nutrient Supply (IPNS), and the 4R stewardship principle of applying the right source at the right rate, time, and place. Through documented field experiences and supportive government policy, it argues that nutrient management guided by soil testing raises yields, lowers input costs, protects the environment, and safeguards long-term soil health.

Keywords: soil health card, soil testing, balanced fertilization, nutrient management, STCR, integrated plant nutrient supply, soil fertility.

1. Introduction

Every good harvest begins not with the seed but with the soil beneath it. Soil supplies crops with water, air, and the mineral nutrients they need to grow, and it teems with microbes that quietly recycle those nutrients season after season. For a farmer, healthy soil is the single most valuable asset

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on the farm. Yet across much of India, this asset is under strain. Decades of intensive cropping, coupled with heavy and often unbalanced use of chemical fertilizers, have depleted organic matter, created nutrient imbalances, and left many fields tired and less responsive.

A large part of the problem is that fertilizer has often been applied by habit rather than by need. Many farmers pour on urea generously while neglecting phosphorus, potassium, and the micronutrients that crops also require. The result is wasted money, lower fertilizer-use efficiency, polluted water, and, paradoxically, stagnant or falling yields. The remedy is simple in principle: test the soil first, then feed the crop exactly what it lacks. To put this idea into every farmer's hands, the Government of India launched the Soil Health Card Scheme in 2015. This article explains how soil testing and card-based recommendations work, and how they form the basis of sound, science-led nutrient management.

- The Soil Health Card Scheme was launched on 19 February 2015 at Suratgarh, Rajasthan, under the motto 'Swasth Dharaa, Khet Haraa' Healthy Earth, Healthy Farm. Every 19 February is now observed as Soil Health Card Day.

2.1 What Is a Soil Health Card?

A Soil Health Card is a printed (and digital) report that tells a farmer the condition of the soil in a particular field. It records the levels of the most important soil nutrients and properties and, crucially, gives crop-wise recommendations on how much of each fertilizer and amendment to apply. In other words, it converts a laboratory soil test into a plain-language prescription the farmer can act on. Under the scheme, a card is issued for each landholding on a regular cycle so that changes in soil fertility can be tracked over time, and the recommendations updated accordingly. The cards are generated through a national portal in a standard format and made available in major regional languages.

2.2 Why Testing the Soil Matters

Soils differ enormously from one field to the next; even neighboring plots can vary in pH, organic carbon, and nutrient reserves. A fertilizer dose that is right for one field may be wasteful or inadequate for another. The old practice of applying the same 'blanket' recommendation across a whole district ignores this variability. It commonly leads to two opposite errors: over-application of nitrogen, which is costly and pollutes groundwater, and under-application of phosphorus, potassium, sulphur, and micronutrients, which quietly caps yields. Soil testing replaces guesswork with evidence. By measuring what the soil actually holds, it allows fertilizer to be matched to the genuine gap between what the crop needs and what the soil can supply.

Expert Advice

Fertilizer is medicine for the crop, and like any medicine it works best at the right dose. Applying more urea than the soil test recommends rarely raises yield; it usually just raises cost and harms the soil. Test first, then feed.

2.3 The Twelve Parameters and How to Read the Card

A Soil Health Card reports the soil's status across twelve parameters. These fall into a few simple groups: the primary macronutrients needed in large amounts, the secondary nutrient sulfur, a set of micronutrients required in tiny but vital quantities, and three physical-chemical properties that shape how well nutrients become available to the crop.

Group	Parameters	What They Tell the Farmer
Primary macronutrients	Nitrogen (N), Phosphorus (P), Potassium (K)	The main nutrients driving growth, root and grain formation
Secondary nutrient	Sulfur (S)	Important for oilseeds, pulses and protein quality
Micronutrients	Zinc (Zn), Iron (Fe), Manganese (Mn), Copper (Cu), Boron (B)	Needed in small amounts; deficiencies sharply cut yield and quality
Soil properties	pH, Electrical Conductivity (EC), Organic Carbon (OC)	Acidity/alkalinity, salinity, and soil fertility/health status

Reading the card is straightforward. The pH value shows whether the soil is acidic, neutral, or alkaline, which decides whether lime or gypsum is needed and how freely nutrients dissolve. Electrical conductivity flags salinity problems. Organic carbon is a snapshot of soil health and biological life; low values signal a need for compost, manures, or green manuring. Each nutrient is rated as low,

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medium, or high, and the accompanying recommendation converts these ratings into specific quantities of fertilizer for the chosen crop.

2.4 From Test to Practice: Nutrient Management Based on Testing

The card is only the beginning; its real value lies in what the farmer does next. Soil-test-based nutrient management rests on a few well-established principles.

The first is balanced fertilization, supplying all the nutrients a crop needs in the correct proportion, not merely nitrogen alone. Correcting a hidden zinc or sulfur deficiency, for instance, can lift the response to nitrogen and phosphorus dramatically. The second is the Soil Test Crop Response (STCR) approach, a scientific method that uses soil test values together with the crop's nutrient demand for a target yield to calculate a precise fertilizer dose. Compared with blanket recommendations, STCR consistently produces higher yields, better nutrient-use efficiency, and greater profit, while conserving soil fertility.

The third principle is Integrated Plant Nutrient Supply (IPNS) — combining chemical fertilisers with organic sources such as farmyard manure, compost, green manures, and biofertilisers. Organic matter improves soil structure, feeds soil microbes, and releases nutrients slowly, making the whole system more resilient. Underpinning all of these is the 4R stewardship idea: apply the right nutrient source, at the right rate, at the right time, and in the right place. Splitting nitrogen into several doses through the season, placing fertiliser near the root zone, and timing applications to crop demand all raise efficiency and cut losses.

> **Farmer's Tip**
>
> Do not ignore the micronutrients. A small, inexpensive dose of zinc or boron, applied when the card recommends it, often pays back many times over in extra yield — especially in rice, wheat, pulses, and oilseeds.

2.5 Benefits of Soil-Test-Based Nutrient Management

When farmers move from habit-based to test-based fertilization, the gains are both economic and environmental.

Benefit	How It Helps the Farmer and the Land
Higher yields	Correcting hidden deficiencies unlocks the crop's full potential
Lower input costs	No money wasted on nutrients the soil already has in plenty
Better nutrient-use efficiency	More of every kilogram of fertilizer reaches the crop
Improved soil health	Balanced feeding and organic inputs rebuild fertility over time
Environmental protection	Less nitrate leaching, reduced pollution of water and air
Informed crop choice	Matching crops to soil pH and salinity reduces the risk of failure

2.6 How to Collect a Reliable Soil Sample

A soil test is only as good as the sample it is based on, and this is one step the farmer directly controls. A careless sample can misrepresent an entire field and lead to the wrong recommendation. A few simple practices make the result trustworthy:

- Divide the farm into uniform units, keeping areas that differ in color, slope, or past cropping separate.
- From each unit, collect small amounts of soil from eight to ten spots moving in a zig-zag pattern across the field.
- At each spot, remove surface litter and take soil from the plow layer, roughly the top 15 centimeters for most field crops.
- Mix all the sub-samples together, remove stones and roots, and reduce the heap to about half a kilogram for the laboratory.

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- Sample when the field is neither waterlogged nor bone-dry, and avoid spots near field bunds, manure heaps, or recently fertilized strips.

Correct labeling, with the farmer's name, field details, and the crop to be grown, ensures the recommendation that comes back is genuinely tailored to that field.

2.7 Challenges and Limitations

Soil health cards are a powerful tool, but they are not automatic. Their impact depends on how well the system works on the ground. Testing laboratories must be adequate in number and reliable in quality, and samples must be collected properly, because a poorly drawn sample gives a misleading result. Cards must reach farmers in time for the sowing season and be explained in language they understand, since a card that is filed away unread changes nothing. Recommendations also need to be updated as soils change, and farmers must be encouraged to combine the advice with organic inputs rather than treating fertilizer as the only answer. Bridging the gap between a printed recommendation and a change in field practice remains the central challenge, and it is where extension workers and Krishi Vigyan Kendras play a vital role.

3. Case Studies: Testing in Action

The value of soil testing is clearest in the fields where farmers have embraced it.

3.1 Correcting Micronutrient Hunger

Across the rice–wheat belt of northern India, widespread zinc deficiency long held back yields even where farmers applied ample nitrogen and phosphorus. Once soil tests revealed the shortage, targeted zinc application became a routine recommendation on soil health cards. Farmers who added the recommended zinc frequently reported healthier crops and measurable yield gains from a very small additional cost, a textbook example of how a single corrected deficiency transforms results.

3.2 STCR Field Trials

Long-term experiments conducted by agricultural research institutions have compared soil-test-based STCR recommendations, combined with farmyard manure, against the standard blanket dose. Across a range of crops- soybean, sunflower, chili, aerobic rice, and millets, the STCR-with-manure approach delivered significantly higher yields, greater nutrient uptake, and better soil quality than the general recommendation. These trials provide the scientific backbone for the card-based advice reaching farmers.

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3.3 Cutting Costs Through Balanced Feeding

Many farmers who once relied almost entirely on urea have found, after testing, that their soils were already rich in nitrogen but short on potassium or sulphur. Rebalancing their fertilizer accordingly reduced wasteful urea use, lowered their input bill, and improved crop quality, showing that better nutrition and lower cost can go hand in hand.

4. Policy Support and Government Initiatives

The Soil Health Card Scheme sits within a wider policy framework aimed at sustainable soil and nutrient management.

- **Soil Health Card Scheme**: Provides field-specific soil test reports and crop-wise fertilizer recommendations to farmers on a regular cycle, now delivered through a national portal and mobile application.
- **Integration with Rashtriya Krishi Vikas Yojana (RKVY):** The soil health and fertility component supports decentralized soil testing and laboratory infrastructure across states.
- **Support for soil testing laboratories:** Financial assistance encourages farmers and rural youth to set up village-level testing labs, creating employment while expanding access.
- **Neem-coated urea and Nutrient Based Subsidy (NBS)**: Policy measures that improve nitrogen-use efficiency and promote balanced use of a range of fertilizers.
- **Krishi Vigyan Kendras and ICAR:** Develop soil-test-based recommendations, run demonstrations, and train farmers in balanced and integrated nutrient management.

5. Key Takeaways

- Healthy soil is a farmer's most valuable asset; imbalanced fertilizer use quietly destroys it.
- A Soil Health Card turns a laboratory soil test into a clear, crop-wise fertilizer prescription.
- The card reports twelve parameters N, P, K, S, five micronutrients, and pH, EC, and organic carbon.
- Test the soil first, then apply balanced doses of all needed nutrients, not nitrogen alone.

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- Use the STCR approach and combine fertilisers with organic manures and biofertilisers (IPNS).
- Follow the 4Rs: right source, right rate, right time, right place.
- Collect samples carefully, correct micronutrient deficiencies, and act on the card in the field.

6. Conclusion

Soil is a living, finite resource, and the way it is nourished today shapes the harvests of tomorrow. For too long, fertilizer has been applied by guesswork, wasting money, degrading soils, and polluting the environment without delivering the yields farmers deserve. The Soil Health Card offers a better path: it lets the soil speak, and it turns that voice into clear, crop-specific advice.

Nutrient management based on testing, balanced fertilization, the STCR approach, integrated organic and inorganic inputs, and the discipline of the 4Rs consistently produces more grain at lower cost while rebuilding the soil rather than mining it. Realizing this promise requires reliable laboratories, timely cards, and above all farmers who read, understand, and act on the recommendations, supported by extension services on the ground. If the card in a farmer's hand becomes a decision in the field, Indian agriculture can feed its people, protect its precious soils, and grow more sustainably with every season. Healthy soil, after all, is the quiet foundation of a healthy farm and a food-secure nation.

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The hidden workforce beneath your feet: Role of soil microorganisms in sustainable crop production

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Abstract

Beneath every productive field lies a workforce far larger and more consequential than most farmers ever see: billions of bacteria, fungi, protozoa, and other microorganisms per gram of soil, quietly performing the nutrient cycling, disease suppression, and structure-building work that crops depend on. Decades of intensive tillage and heavy agrochemical use have often overlooked, and in many cases actively damaged, this living infrastructure. This article surveys the major functional groups of soil microorganisms-nitrogen-fixing bacteria, mycorrhizal fungi, decomposers, and plant growth-promoting rhizobacteria and explains the specific services each provides to crop production. It examines how common farming practices affect microbial communities for better or worse, reviews the growing role of microbial inoculants and biofertilizers in Indian agriculture, and profiles field-level evidence of microbiome-based approaches improving yield and resilience. It closes by considering what farmers and extension workers can do to actively protect and rebuild this hidden workforce.

Introduction

Pull up a handful of healthy farmland soil, and you are, without realizing it, holding one of the most densely populated habitats on Earth. A single gram, roughly a teaspoon of fertile agricultural soil can contain billions of bacterial cells, several kilometers of fungal hyphae, and thousands of species of protozoa, nematodes, and other microscopic life, most of which remain formally unidentified even

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today. For most of agricultural history, this community worked in the background, its contributions folded invisibly into what farmers simply called "good soil." Modern soil science has begun to make that invisible workforce visible, and in doing so, has reshaped how researchers think about everything from fertilizer efficiency to disease control to a crop's ability to withstand drought.

- A single gram of healthy agricultural soil can contain more microorganisms than there are people on Earth.
- Mycorrhizal fungi form symbiotic relationships with the roots of the vast majority of land plant species, including most major crops.
- Nitrogen-fixing bacteria associated with legume crops can supply a substantial share of a crop's nitrogen needs without any synthetic fertilizer input.
- Intensive tillage and prolonged chemical fertilizer use have been shown to measurably reduce soil microbial diversity and biomass over time.

Meet the Underground Workforce

Soil microorganisms are not a single, uniform community but a collection of distinct functional groups, each performing different jobs that collectively keep a field productive. Understanding these groups separately helps explain why damaging one part of the soil food web, through excessive tillage, fumigation, or prolonged chemical input use, can have consequences that ripple across functions a farmer may not immediately connect to soil biology at all.

Functional Group	Primary Role	Example Organisms
Nitrogen-fixing bacteria	Convert atmospheric nitrogen into plant-usable forms	Rhizobium, Azotobacter, Azospirillum
Mycorrhizal fungi	Extend root reach for water and phosphorus uptake	Arbuscular mycorrhizal fungi (Glomus spp.)
Decomposers	Break down organic matter, releasing nutrients	Saprophytic fungi, actinomycetes

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Functional Group	Primary Role	Example Organisms
Plant growth-promoting rhizobacteria (PGPR)	Produce growth hormones, suppress pathogens	Pseudomonas, Bacillus species
Predatory protozoa and nematodes	Regulate bacterial and fungal populations	Amoebae, free-living nematodes

Nitrogen Fixation: Nature's Fertilizer Factory

Perhaps no microbial service is better known to farmers than biological nitrogen fixation, even if the underlying biology often goes unexplained. Rhizobium bacteria, living in nodules on the roots of legume crops such as pulses, soybean, and groundnut, convert inert atmospheric nitrogen gas into ammonia, a form the plant can use directly a service that, under well-nodulated conditions, can supply a meaningful share of a legume crop's total nitrogen requirement without any synthetic fertilizer application. Free-living nitrogen fixers such as Azotobacter and associative fixers such as Azospirillum extend a smaller but still valuable version of this service to non-legume crops including cereals, when soil conditions and inoculation practices support their activity.

Mycorrhizal Fungi: The Root Network Extenders

Arbuscular mycorrhizal fungi form one of the oldest and most widespread partnerships in the plant kingdom, colonizing the roots of the large majority of crop species and extending a network of fine fungal filaments, called hyphae, far beyond the reach of the root system itself. This network dramatically increases the effective surface area available for water and nutrient absorption, particularly for phosphorus, an element that moves slowly through soil and is often poorly accessible to roots alone in phosphorus-fixing soils common across much of India.

In exchange for this expanded uptake capacity, the plant supplies the fungus with sugars produced through photosynthesis a genuinely mutualistic trade. Crops with strong mycorrhizal associations often show improved drought tolerance as well, since the extended hyphal network can access soil moisture in pockets a root system alone would miss, an increasingly relevant benefit as rainfall patterns grow less predictable.

DID YOU KNOW?

- Mycorrhizal hyphal networks can sometimes connect the root systems of multiple neighboring plants, allowing limited transfer of nutrients and even chemical distress signals between them.
- Excessive tillage physically shreds fungal hyphal networks, which can take multiple seasons to rebuild even after tillage is reduced or stopped.
- Some plant growth-promoting rhizobacteria produce compounds that directly suppress soil-borne fungal pathogens, functioning as a natural biological control layer.

Decomposers and Plant Growth-Promoting Bacteria

While nitrogen fixers and mycorrhizal fungi tend to attract the most attention, decomposer organisms' saprophytic fungi, actinomycetes, and a wide range of bacteria perform the essential background work of breaking down crop residue, manure, and other organic matter into humus and available nutrients that feed the rest of the soil food web. Without an active decomposer community, organic amendments added to a field would largely remain inert rather than releasing their nutrients over time.

Plant growth-promoting rhizobacteria, a broad category that includes several Pseudomonas and Bacillus species, contribute through multiple mechanisms simultaneously: producing plant growth hormones that stimulate root development, solubilizing soil-bound phosphorus and potassium into forms roots can absorb, and in some cases directly suppressing pathogenic fungi and bacteria through competition or antibiotic-like compounds. This multi-functional profile has made several PGPR strains a growing focus of commercial biofertilizer and biocontrol product development in Indian agriculture.

How Farming Practices Shape the Microbial Community

Soil microbial communities are remarkably responsive to management decisions, for better and for worse. Excessive tillage physically disrupts fungal hyphal networks and exposes previously protected organic matter to rapid oxidation, both of which tend to reduce microbial biomass and diversity over successive seasons. Prolonged, heavy use of certain fungicides and broad-spectrum pesticides can suppress beneficial fungi and bacteria alongside the pests and pathogens they are

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intended to target, since many chemical controls do not distinguish sharply between harmful and beneficial soil organisms.

Microbial Inoculants and Biofertilizers in Indian Agriculture

Recognizing the productivity value of a healthy soil microbiome, Indian agricultural research and extension systems have increasingly promoted microbial inoculants, commercially produced formulations of beneficial bacteria or fungi applied to seed or soil to supplement or restore populations that may be depleted in intensively farmed fields. Rhizobium inoculants for pulse crops, Azotobacter and Azospirillum for cereals, phosphate-solubilizing bacteria, and mycorrhizal inoculants are now widely available through state agriculture departments and Krishi Vigyan Kendras, often at subsidized cost as part of broader sustainable agriculture promotion efforts.

Nature's Own Disease Control: Suppressive Soils

Among the more striking phenomena in soil microbiology is the existence of what researchers call suppressive soils, fields where a particular soil-borne disease consistently fails to establish or causes far less damage than expected, not because the pathogen is absent but because the resident microbial community actively keeps it in check. This suppression typically arises from a combination of direct competition for space and nutrients, antibiotic-like compounds produced by certain bacteria and fungi, and induced resistance responses triggered in the plant itself by beneficial microbial colonization of the root zone.

Suppressive soil effects have been documented against several major soil-borne pathogens affecting Indian field and horticultural crops, including certain wilt-causing fungi and root-knot nematodes. What makes this phenomenon particularly valuable from a sustainable agriculture standpoint is that, unlike a chemical fungicide application that must be repeated each season, a well-established suppressive microbial community can provide disease protection that persists and even strengthens over time provided farming practices do not disrupt the microbial populations responsible for it. This is one of the more compelling practical arguments for minimizing broad-spectrum soil fumigation and excessive fungicide use except where genuinely necessary, since these interventions can inadvertently dismantle a disease suppression system that would otherwise be working in the farmer's favor at no ongoing cost.

Building Climate Resilience Through the Soil Microbiome

As climate variability increases the frequency of drought spells and heat stress events, researchers have paid growing attention to the specific role soil microorganisms play in helping crops withstand these pressures. Certain rhizobacteria and mycorrhizal fungi have been shown to improve plant drought tolerance through several mechanisms: producing compounds that help plant cells retain water under stress, improving root architecture to access deeper soil moisture, and in some documented cases, triggering physiological changes in the plant that reduce water loss through leaf surfaces during periods of heat stress.

This has opened a research frontier sometimes described as microbiome-assisted stress tolerance, in which specific microbial strains are being screened and selected not primarily for growth promotion under normal conditions, but specifically for their ability to buffer crops against drought, heat, or salinity stress. While much of this work remains at the research and pilot stage rather than widespread commercial application in India, it represents a promising complement to breeding-based approaches to climate resilience, offering a route to stress tolerance that works with a crop's existing genetics rather than requiring a new variety altogether.

Voices from the Field: Two Illustrative Cases

Punjab: Restoring Microbial Activity After Intensive Cropping

Long-term soil monitoring in parts of Punjab's intensively cropped rice-wheat belt has documented measurable declines in soil microbial biomass and diversity after decades of continuous tillage-heavy cultivation and heavy chemical input use. Demonstration trials introducing residue retention, reduced tillage, and microbial inoculant use alongside existing practices have shown recovering microbial activity within a few seasons, alongside modest but consistent improvements in nutrient-use efficiency, evidence that microbial recovery, while gradual, is achievable even in intensively managed systems given the right combination of practices.

Karnataka: Biofertilizer Adoption in Pulse Cultivation

Extension-led promotion of Rhizobium inoculant use in pulse-growing districts of Karnataka has demonstrated how a low-cost, simple-to-apply microbial input can meaningfully reduce farmers' dependence on purchased nitrogen fertilizer for legume crops. Farmer field demonstrations comparing inoculated and uninoculated plots, run through local KVKs, have been particularly effective at building farmer confidence in a technology that, unlike a visible fertilizer bag, requires some trust that an invisible biological process is actually taking place underground.

Challenges in Bringing Soil Biology to the Field

Despite growing scientific interest and policy support, translating soil microbiology research into consistent field-level benefit faces real obstacles. Microbial inoculant quality control remains inconsistent across manufacturers, with viable organism counts sometimes falling well below labeled specifications by the time a product reaches a farmer, particularly where cold-chain storage is not maintained. Soil-specific variation is substantial: an inoculant strain that performs well in one soil type or agro-climatic zone may show little benefit in another, making blanket recommendations less reliable than location-specific testing and guidance.

- Inconsistent quality control and viability of commercial microbial inoculants
- Limited farmer awareness of how storage and handling affect inoculant performance
- Soil- and climate-specific variation in which microbial strains perform best
- Continued reliance on tillage and chemical inputs that work against microbial recovery
- Limited extension capacity for soil biology-specific advisory support compared to chemical input recommendations

Conclusion

The soil beneath a farmer's feet is not an inert growing medium but a living system, dense with organisms performing work that would otherwise require far greater quantities of purchased fertilizer and chemical crop protection to replicate. Nitrogen-fixing bacteria, mycorrhizal fungi, decomposers, and plant growth-promoting rhizobacteria each contribute a distinct service, and together they form an underground infrastructure that intensive, disturbance-heavy farming has often eroded without farmers fully realizing the cost. As microbial inoculant technology matures and extension systems build the capacity to translate soil biology into practical field guidance, this hidden workforce is increasingly being recognized for what it has always been: not a footnote to sustainable crop production, but one of its central pillars.

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Climate-Smart Soil and Water Conservation for Drought-Prone Districts

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Abstract

Drought-prone districts, spread widely across India's rainfed and semi-arid regions, face erratic rainfall, degraded soils, and falling groundwater, and climate change is making these stresses sharper and more frequent. For the small and marginal farmers who dominate these areas, conserving soil and water is not a luxury but a matter of survival. This article explains what makes a district drought-prone and sets out a practical, climate-smart toolbox of soil and water conservation measures. It distinguishes in-situ practices that hold rain where it falls contour bunding, trenches, mulching, conservation tillage, and cover crops from ex-situ structures that store and recharge water, such as farm ponds, check dams, and percolation tanks. It places these within the watershed approach, which treats an entire ridge-to-valley landscape as a single unit managed by the community, and pairs them with efficient irrigation and drought-tolerant crops. Drawing on documented field successes and supportive national programmes, it argues that well-planned conservation can drought-proof farms, recharge aquifers, restore soils, and secure rural livelihoods.

Keywords: *drought-prone districts, soil and water conservation, watershed management, rainwater harvesting, climate-smart agriculture, groundwater recharge, rainfed farming*

1. Introduction

In large parts of India, the difference between a good year and a ruinous one comes down to a few weeks of rain. Across the semi-arid stretches of the Deccan, the dry districts of Rajasthan and Gujarat, the Bundelkhand plateau, and the rain-shadow tracts of the peninsula, farming is a gamble against an

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uncertain sky. When the monsoon is kind, fields flourish; when it fails or turns fickle, crops wither, wells fall silent, and families slide into hardship. These are India's drought-prone districts, and they are home to millions of small and marginal farmers who depend almost entirely on rainfall.

Climate change is raising the stakes. Rainfall is becoming more erratic, concentrated into fewer, heavier bursts separated by longer dry spells, while rising temperatures increase evaporation and crop water demand. At the same time, decades of over-pumping have driven groundwater tables steadily downward, and unchecked runoff continues to strip fertile topsoil from sloping, ill-protected fields. In this setting, conserving soil and water is the single most powerful thing a farmer or a community can do. This article explains how climate-smart soil and water conservation works, and how it can turn fragile, thirsty landscapes into resilient, productive ones.

2.1 Understanding Drought-Prone Districts

A drought-prone district is one where rainfall is not only low but unreliable, so that crop failure from water shortage is a recurring risk rather than a rare accident. Several features tend to travel together in such areas: annual rainfall that is modest and highly variable from year to year; a heavy dependence on the monsoon with little or no assured irrigation; soils that are often shallow, sloping, and low in organic matter, and therefore quick to lose both water and nutrients; and falling groundwater tables that leave few reserves to fall back on. Because most farmers in these districts are smallholders with limited resources, a single failed season can be devastating. Conservation of soil and water directly attacks the root of the problem by keeping more rain on the farm and more soil in place.

2.2 What Is Climate-Smart Soil and Water Conservation?

Climate-smart soil and water conservation means managing land and rainfall in ways that simultaneously raise productivity, build resilience to climate stress, and protect the natural resource base for the future. The guiding idea is simple: slow the water down, spread it out, and sink it in. Instead of letting rain rush off the surface carrying away soil and leaving fields parched days later, conservation practices help rainfall soak into the ground, recharge wells, and remain available to crops through dry spells. The same measures that hold water in the soil also hold the soil itself, checking the erosion that quietly robs drought-prone land of its fertility.

2.3 In-Situ Measures: Holding Rain Where It Falls

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In-situ practices conserve moisture and soil right in the field, before water has a chance to run off. They are usually low-cost and within the reach of individual farmers.

Practice	**How It Conserves Soil and Water**
Contour bunding & contour trenches	Small earthen banks and trenches across the slope slow runoff, trap silt, and let water soak in
Conservation / minimum tillage	Reduced ploughing keeps soil covered and structured, cutting erosion and evaporation
Mulching with crop residue	A protective cover checks evaporation, moderates soil temperature, and suppresses weeds
Cover crops & green manures	Living roots bind the soil, add organic matter, and improve infiltration
Broad-bed-and-furrow / ridge-furrow	Shapes the land to store rain in furrows and drain excess safely, protecting the crop
Field bunding & land levelling	Retains rainwater within the plot and spreads it evenly for uniform soaking

Farmer's Tip

Never leave the soil bare during the dry months. A blanket of crop residue or a cover crop is like a roof over your field, it keeps moisture in, temperature down, and precious topsoil from blowing or washing away.

2.4 Ex-Situ Measures: Storing and Recharging Water

Ex-situ structures capture the water that does run off and store it for later use or guide it underground to recharge aquifers. These are often built collectively along the land's natural drainage lines. Farm ponds collect runoff for life-saving supplemental irrigation during dry spells. Check dams and gully plugs built across streams and eroding channels slow the flow, trap silt, and let water percolate. Percolation tanks and recharge shafts are designed specifically to send water down into the

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ground, lifting the level of nearby wells. Restored traditional structures, the tanks, johads, and village ponds that earlier generations built, remain remarkably effective when revived. Together, these structures convert destructive runoff into a stored asset.

2.5 The Watershed Approach

The most effective way to organize all these measures is the watershed approach. A watershed is simply the area of land that drains rainwater to a common point, such as a stream or pond. Treating this whole unit together, rather than field by field, allows conservation to be planned from the ridge at the top to the valley at the bottom, so that water is intercepted, slowed, and stored at every stage of its journey downhill. Because the benefits and the water are shared, the watershed approach works best when the whole community plans and maintains the structures together. Done well, it raises groundwater levels, extends the cropping season, supports livestock and horticulture, and lifts entire villages out of chronic water stress.

2.6 Efficient Water Use and Smart Crop Choices

Conserving water is only half the task; using it wisely is the other. Once rain has been harvested and stored, drip and sprinkler irrigation stretch every drop far further than flooding a field. Choosing the right crops matters just as much: drought-tolerant and short-duration varieties escape or withstand dry spells, while shifting from water-guzzling crops toward pulses, millets, oilseeds, and dryland horticulture reduces water demand and spreads risk. Intercropping and crop diversification ensure that if one crop fails, another survives. Matching the crop to the district's rainfall and soil rather than forcing thirsty crops onto thirsty land is itself a powerful conservation measure.

2.7 Benefits of Climate-Smart Conservation

Benefit	How It Helps the Farmer and the Land
More soil moisture	Crops survive dry spells; the effective growing season lengthens
Groundwater recharge	Wells last longer, supporting a second crop and drinking water
Reduced soil erosion	Fertile topsoil and its nutrients stay in the field

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Benefit	How It Helps the Farmer and the Land
Higher, steadier yields	Reliable moisture and healthy soil raise and stabilise production
Diversified livelihoods	Water and fodder support livestock, fisheries, and horticulture
Climate resilience	Farms and villages withstand droughts and erratic rainfall better

3. Case Studies: Conservation That Changed Districts

The power of soil and water conservation is best seen where drought-prone communities have transformed their fortunes.

3.1 Ralegan Siddhi and Hiware Bazar, Maharashtra

Two neighboring villages in drought-prone Ahmadnagar district became national symbols of what watershed work can achieve. Through community-led rainwater harvesting, check dams, contour trenching, tree planting, and strict rules against water-hungry crops and open grazing, they raised their groundwater, greened their fields, and moved from scarcity and out-migration to prosperity. Their success showed that discipline and collective effort matter as much as any structure.

3.2 The Kothapally Watershed, Telangana

The Kothapally watershed, developed with support from ICRISAT, became a widely studied model of integrated, science-based conservation in the semi-arid tropics. A combination of in-situ measures and water-harvesting structures improved groundwater recharge, allowed farmers to diversify into higher-value crops, and raised incomes, demonstrating how research and farmer participation together can drought-proof a landscape.

3.3 Bundelkhand's Watershed Revival

Long regarded as one of India's most drought-stricken regions, parts of Bundelkhand have seen striking recovery through watershed interventions. After water-harvesting structures were put in place, a single high-intensity rainfall event was captured rather than lost, infiltration improved, and

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groundwater levels rose by several metres, expanding the area farmers could cultivate. The region is now studied as a model for replication elsewhere.

3.4 Reviving Traditional Water Harvesting in Rajasthan

In the dry districts of Rajasthan, community efforts to revive traditional johads and tanks, supported by state water-conservation campaigns, have recharged wells and returned water to villages that had long run dry. These efforts underline that some of the best climate-smart solutions are age-old techniques, revived and combined with modern planning.

4. Policy Support and Government Initiatives

A strong policy framework backs soil and water conservation in India's drought-prone districts.

- Watershed Development Component of PMKSY (WDC-PMKSY 2.0): The flagship watershed programme for rainfed and degraded lands, targeting semi-arid and arid districts with soil conservation, rainwater harvesting, and livelihood support during 2021–2026.
- Atal Bhujal Yojana (Atal Jal): A community-led groundwater management scheme launched in 2019 for water-stressed areas across seven states, focusing on demand management and behavioral change.
- Pradhan Mantri Krishi Sinchayee Yojana (PMKSY): Promotes efficient irrigation under 'per drop more crop', supporting drip and sprinkler systems that conserve harvested water.
- Convergence with MGNREGA: Rural employment funds are widely used to build check dams, farm ponds, and other conservation structures, combining livelihoods with land treatment.
- NICRA and district contingency plans: ICAR's climate-resilient agriculture programme identifies vulnerable districts and prepares location-specific plans, including conservation and drought-management measures.

5. Conclusion

Drought is one of the oldest adversaries of the Indian farmer, and climate change is sharpening its edge. Yet the experience of transformed villages from Maharashtra to Bundelkhand to Rajasthan proves that drought-prone need not mean drought-doomed. Where communities have chosen to conserve, holding their soil, harvesting their rain, and recharging their groundwater, dry and despairing landscapes have turned green and productive.

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Climate-smart soil and water conservation is neither exotic nor unaffordable. It rests on simple, proven measures: bunds and trenches on the slopes, ponds and check dams in the valleys, mulch and cover on the fields, and efficient irrigation for the harvested water, all knitted together by the logic of the watershed and the strength of the community. Backed by supportive national programmes and guided by local knowledge and science, these measures can drought-proof India's most vulnerable districts. The rain that once ran away, carrying the soil with it, can instead be caught, stored, and put to work — securing not just the next harvest, but the future of the land itself.

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CLIMATE-SMART AGRICULTURE: ***The Future of Sustainable Food Production***

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Abstract

Climate change is reshaping the conditions under which food must be produced, placing unprecedented pressure on farming systems that are expected to feed a growing population while reducing their own environmental footprint. Climate-Smart Agriculture (CSA) offers a framework for reconciling these demands through three interlinked goals: sustainably raising productivity, strengthening farmer resilience to climate variability, and reducing or sequestering greenhouse gas emissions where feasible. This article examines the rationale for CSA in the Indian context, surveys widely adopted climate-smart practices such as direct-seeded rice, zero-tillage, and climate-resilient crop varieties, and draws on field experience from Punjab, Maharashtra, and Odisha to illustrate both the promise and the practical barriers to adoption. It further considers the role of digital tools, financial innovation, and equity in extending these benefits to marginalized farming communities, before outlining institutional and policy shifts needed to move Climate-Smart Agriculture from isolated pilots to mainstream practice.

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Introduction

Farming has never faced a moment quite like this one. Rising temperatures, erratic monsoons, shrinking water tables, and increasingly frequent extreme weather events are rewriting the rules that generations of farmers once relied on. At the same time, the world must feed nearly ten billion people by 2050 without exhausting the very soil, water, and biodiversity that make food production possible in the first place. Climate-Smart Agriculture (CSA) has emerged as the framework that tries to reconcile these competing demands: producing more, protecting farmers from climate shocks, and cutting agriculture's own contribution to the problem, all at once.

QUICK FACTS

- Agriculture, forestry, and other land use contribute close to a quarter of global greenhouse gas emissions.
- India's agriculture sector employs nearly half the workforce but remains highly vulnerable to monsoon variability.
- The concept of Climate-Smart Agriculture was formally introduced by the FAO in 2010 at The Hague Conference on Agriculture, Food Security and Climate Change.
- CSA is not a single technology but an approach that integrates practices across productivity, adaptation, and mitigation goals.

What exactly is Climate-Smart Agriculture?

Climate-Smart Agriculture is best understood not as a fixed set of tools but as a way of thinking about farming decisions. It asks a simple question before adopting any practice, input, or policy: does this help farmers produce food more efficiently, does it help them cope with a changing climate, and does it reduce or avoid greenhouse gas emissions? A practice that scores well on all three counts is considered climate-smart; most real-world interventions involve trade-offs that extension workers and policymakers must weigh carefully.

The approach rests on three mutually reinforcing pillars, often summarised as the “triple win” of CSA.

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The Three Pillars

Pillar	What It Means	Example on the Ground
Productivity	Sustainably increasing food and income without expanding the resource base	Precision nutrient management raising yield per hectare
Adaptation	Building resilience to climate variability and extremes	Drought-tolerant seed varieties and community weather advisories
Mitigation	Reducing or sequestering greenhouse gas emissions where possible	Zero-tillage reducing residue burning and fuel use

The Global Backdrop: A Warming Planet, A Straining Food System

The urgency behind Climate-Smart Agriculture cannot be separated from the broader trajectory of global warming. Average global temperatures have already risen well over one degree Celsius above pre-industrial levels, and the Intergovernmental Panel on Climate Change has repeatedly warned that agriculture sits among the sectors most exposed to further warming — even as it remains one of the sectors most capable of contributing to solutions through soil carbon sequestration, reduced methane emissions, and smarter land use.

Three interlinked pressures define this moment for global food systems. First, yields for staple cereals in several regions are already showing signs of climate-related stagnation, even as population and dietary demand continue to rise. Second, water availability is becoming less predictable, with some regions facing more frequent droughts while others contend with flooding and soil salinisation from sea-level rise. Third, agriculture itself is a meaningful source of the problem it must adapt to, contributing methane from livestock and paddy cultivation, nitrous oxide from fertiliser overuse, and carbon dioxide from land-use change and deforestation. Climate-Smart Agriculture is, in effect, an attempt to break this feedback loop from within the sector most affected by it.

Global institutions have responded with coordinated frameworks. The FAO's CSA sourcebook, the World Bank's climate-smart investment plans, and various national adaptation plans submitted

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under the Paris Agreement all converge on similar principles — even as the specific technologies and priorities differ sharply between a mechanised farm in temperate Europe and a smallholder plot in semi-arid India.

Why Indian Agriculture Needs This Approach Urgently

India's farming systems sit at the intersection of high climate exposure and high dependence on agriculture for rural livelihoods. Nearly two-thirds of the country's cultivated area still relies on rainfall rather than assured irrigation, which means a delayed monsoon or an unseasonal hailstorm can wipe out an entire season's income for millions of smallholder households. Add to this the fact that groundwater tables in the Indo-Gangetic plains the country's traditional food bowl are falling year after year under the pressure of water-intensive paddy-wheat cropping, and the case for a fundamentally different approach becomes hard to ignore.

The Indian Council of Agricultural Research (ICAR) recognised this early, launching the National Innovations in Climate Resilient Agriculture (NICRA) project to develop and demonstrate climate-resilient technologies across the country's diverse agro-climatic zones. Krishi Vigyan Kendras, working directly with farming communities, have since become the frontline institutions translating research station findings into field-level adoption.

Climate-Smart Practices Making a Difference

A wide range of practices now fall under the CSA umbrella. Some are age-old techniques rediscovered and validated by science; others are the product of recent agronomic and digital innovation. The table below summarises several practices that are gaining traction in Indian farming systems.

Practice	**Primary Benefit**
Direct-seeded rice (DSR)	Cuts water use by up to 30% compared to transplanted paddy
Zero-tillage / conservation agriculture	Reduces fuel use, residue burning, and soil erosion

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Practice	**Primary Benefit**
Laser land leveling	Improves irrigation efficiency and uniform crop stand
System of Rice Intensification (SRI)	Increases yield while lowering water and seed requirements
Agroforestry and farm bunding	Diversifies income and sequesters carbon in tree biomass
Climate-resilient crop varieties	Tolerates drought, flood, or salinity stress
Solar-powered micro-irrigation	Cuts diesel dependence and improves water-use efficiency
Weather-based agro-advisories	Enables timely sowing, spraying, and harvest decisions

What unites these practices is that none of them demand farmers choose between yield and sustainability. Direct-seeded rice, for instance, does not merely save water — in well-managed fields it also reduces labour costs and methane emissions from flooded paddies, illustrating how a single change can advance all three CSA pillars simultaneously.

Technology and Data: The Quiet Enablers

Behind many climate-smart success stories sits a less visible layer of digital infrastructure. Satellite-based soil moisture mapping, automated weather stations, and mobile-based pest and disease diagnostic tools have moved from research pilots to genuine field utility over the past decade. Remote sensing now allows extension agencies to flag drought stress or waterlogging across thousands of hectares within days rather than waiting for farmer-reported crop damage, enabling faster relief and advisory response.

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Artificial intelligence and machine learning are beginning to supplement, though not replace, the judgment of experienced agronomists. Yield prediction models trained on historical weather and soil data can help planners anticipate procurement and storage needs months in advance, while chatbot-based advisory services are experimenting with regional-language support to reach farmers who are not comfortable with English-language apps. None of these tools function in isolation; however, their value depends entirely on last-mile trust, a functioning input supply chain, and extension workers capable of translating a dashboard alert into a specific, actionable recommendation for a specific field.

Financial innovation is following a similar trajectory. Weather-index insurance, which pays out based on recorded rainfall or temperature thresholds rather than assessed crop loss, has reduced claim settlement delays that once discouraged farmers from purchasing crop insurance at all. Green bonds and blended finance instruments are also beginning to channel institutional capital toward climate-resilient value chains, though such instruments remain more visible in policy discussion than in a typical smallholder's lived experience so far.

Who Is Left Out: The Equity Question

Any honest account of Climate-Smart Agriculture must reckon with a difficult truth: adoption has so far skewed toward farmers with more land, more capital, and better market access. Women, who perform a substantial share of agricultural labour in India yet own a much smaller share of agricultural land, often have limited say over which technologies a household adopts, even when they are the ones most affected by the resulting workload changes. Tribal and hill farming communities, working smaller and more fragmented plots on marginal land, frequently fall outside the reach of subsidy schemes designed with plains agriculture in mind.

Closing this equity gap is not a side concern to be addressed after the main technical work is done, it is central to whether Climate-Smart Agriculture achieves anything at national scale. Self-help groups and women-led farmer producer organisations have shown that when women are given direct access to training, credit, and decision-making roles, adoption rates and the durability of new practices both improve. Extension strategies that specifically target these groups, rather than assuming information will trickle down through the household, tend to produce more equitable and more lasting results.

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Voices from the Field: Two Illustrative Cases

Punjab - Breaking the Groundwater Trap

Punjab's paddy-wheat system, once the backbone of India's Green Revolution success, is now its most cited example of unsustainable intensification. Decades of free electricity and assured procurement encouraged farmers to grow water-guzzling paddy even in a semi-arid zone. Government-backed diversification programmes, combined with direct-seeded rice and laser levelling demonstrations run through state agricultural universities, have shown that yields can be maintained while cutting irrigation water use substantially — though scaling these gains to the whole state remains a work in progress, constrained by market assurance for alternative crops.

Maharashtra - Farming Through Drought

In the drought-prone districts of Marathwada, watershed development combined with micro-irrigation and drought-tolerant pulse and oilseed varieties has helped many villages stabilise incomes that once swung wildly with the monsoon. Farmer field schools run by local KVKs have played a quiet but crucial role, turning research recommendations into practices farmers trust because they have seen them work on a neighbour's field first.

Odisha - Rebuilding After the Flood

Coastal Odisha's farmers have long lived with cyclones and flash floods, but the frequency of severe events has visibly increased over the past two decades. Submergence-tolerant paddy varieties, developed through public sector rice breeding programmes, have allowed fields to recover crop stand even after being underwater for over a week — a trait that would have meant total crop loss under older varieties. Community seed banks stocking these varieties, maintained with support from local agricultural extension centres, have proven critical in ensuring farmers can resow quickly after a flood event rather than waiting weeks for external seed supply to arrive.

Measuring What Matters: Tracking CSA Outcomes

A recurring challenge in scaling Climate-Smart Agriculture is knowing whether an intervention is actually working, and for whom. Yield data alone can be misleading in a variable climate — a good rainfall year can mask the fact that a farm remains highly vulnerable, while a below-average year following adoption of a resilient practice may still represent a meaningful improvement over what

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would have happened otherwise. Researchers and extension agencies have increasingly turned to a broader basket of indicators to capture this fuller picture.

- Yield stability across seasons, not just average yield in a single year
- Water productivity, measured as output per unit of irrigation water applied
- Input-use efficiency, particularly for nitrogen fertiliser and diesel
- Household income variability as a proxy for climate resilience
- Soil organic carbon trends over multi-year monitoring cycles

Building reliable monitoring systems for these indicators remains a work in progress across most of India's agricultural extension network, and represents one of the clearer opportunities for closer collaboration between universities, state departments of agriculture, and farming communities themselves.

DID YOU KNOW?

- Zero-tillage wheat sown after rice can advance sowing dates by two to three weeks, helping crops escape terminal heat stress before grain filling.
- Agroforestry systems on farm boundaries can offset a meaningful share of a farm's own carbon footprint while providing fuel, fodder, and timber.
- Weather advisory services delivered via mobile phone now reach millions of farmers across India, often in local languages.

The Barriers that Slow Adoption

If climate-smart practices offer such clear benefits, why has adoption remained patchy? The reasons are rarely technical. Upfront costs for equipment such as laser levelers or drip systems remain out of reach for many smallholders without credit or subsidy support. Extension services, though improving, are still stretched thin relative to the number of farm households needing individualized advice. Land fragmentation makes some technologies, like laser leveling, economically unviable on very small plots unless farmers cooperate at a community scale. And deeply held habits shaped by decades of assured procurement for certain crops mean that even well-demonstrated alternatives face resistance until farmers see sustained, not just one-season, benefits.

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- High initial investment cost relative to smallholder cash flow
- Limited access to institutional credit and crop insurance tailored to new practices
- Fragmented landholdings limiting economies of scale for machinery-based solutions
- Uneven last-mile extension outreach, particularly in remote or tribal blocks
- Market and procurement policies still favoring water-intensive traditional crops

Closing the gap between what is technically possible and what is actually practiced on Indian farms will require action on several fronts at once. Extension education has a particularly important role to play here, since technology alone rarely changes behavior; trust, demonstration, and peer learning do.

Strengthening Institutional Support

Credit products and crop insurance schemes need to be redesigned around the risk profile of climate-resilient practices rather than treating them as an afterthought to conventional cropping. Where laser levellers or micro-irrigation units are too costly for individual ownership, custom hiring centres and farmer producer organisations can spread the cost across a community.

Reimagining Extension for a Changing Climate

Extension systems themselves need to evolve. Static, one-size-fits-all advisories are giving way to hyper-local, weather-triggered guidance delivered through mobile applications, community radio, and farmer WhatsApp groups. Krishi Vigyan Kendras and State Agricultural Universities remain indispensable, but their reach multiplies when paired with digital tools and trained para-extension workers drawn from the farming community itself.

Policy Alignment and Farmer Incentives

Perhaps most importantly, procurement and subsidy policy must stop working against climate-smart choices. As long as free power and assured minimum support prices make water-intensive monocultures the financially safest option, no amount of technical demonstration will shift farmer behavior at scale. Aligning incentives through carbon credit pilots for agroforestry, differential power

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pricing, or price support for diversified crops can make the sustainable choice also the rational economic one.

KEY TAKEAWAY

• Climate-Smart Agriculture succeeds only when technology, institutions, and incentives move together; no single intervention can carry the full weight of the transition alone.

Conclusion

Climate-Smart Agriculture is not a distant aspiration reserved for policy documents; it is already visible in the direct-seeded rice fields of Punjab, the drought-hardy plots of Marathwada, and the mobile phones of farmers checking a weather advisory before deciding whether to spray. The task ahead is not to invent new solutions from scratch but to remove the institutional, financial, and informational barriers that keep proven practices from reaching every farmer who needs them. Done well, this transition offers something rare in the climate conversation a genuine triple win where farmers, food systems, and the planet all stand to gain.

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Millets: India's Superfood Revolution for Nutrition and Climate Resilience

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Abstract

Once dismissed as coarse cereals fit mainly for the poorest households, millets are being repositioned at the center of India's food, health, and climate strategy under the banner of Shree Anna. This article traces the science behind their nutritional richness, their unique ability to thrive on minimal water and inputs, and the policy architecture from the 2023 Union Budget renaming them to the Shree Anna Mission and India's successful push for an International Year of Millets, which has driven a steady rise in production. It examines millets' role in addressing anemia and diabetes, their place in school meal and public distribution schemes, the value chains emerging around processing and branding, and the agronomic and market barriers that still limit wider adoption. The article closes with a look at what a genuine millet revolution not just a policy slogan would require of farmers, markets, and consumers alike.

Introduction

For much of the last half-century, Indian agriculture and Indian plates moved in the same direction: away from millets and toward rice and wheat. The Green Revolution delivered food security at a scale the country desperately needed, but it did so by favoring a narrow set of high-yielding, water-intensive crops. Millets jowar, bajra, ragi, and a cluster of so-called minor millets such as kodo, kutki, and foxtail quietly receded from both the farm and the family kitchen, surviving mainly in the driest, most marginal tracts of the country where little else would grow.

That trajectory is now reversing, and not merely as a nostalgic revival. Millets are being reintroduced through a deliberate national strategy that treats them as a solution to three problems at

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once: widespread micronutrient deficiency, the mounting water stress facing Indian agriculture, and the economic vulnerability of smallholder farmers in rainfed regions. The government's decision to rebrand these grains as "Shree Anna," literally, noble grain, signals how central this shift has become to India's food and farm policy.

What Exactly are Millets?

Millets are a group of small-seeded grasses cultivated as cereal crops, distinguished by their short growing cycles and remarkable tolerance for poor soils and erratic rainfall. They are typically divided into major millets sorghum (jowar), pearl millet (bajra), and finger millet (ragi) and a wider group of minor millets, including foxtail, kodo, little, barnyard, proso, and browntop millet, many of which are indigenous to specific tribal and rainfed regions of the country.

Agronomically, millets share several traits that set them apart from rice and wheat: shorter duration crops that can fit into tight cropping windows, deep root systems that draw moisture efficiently from the soil, and natural resistance to many pests and diseases that would otherwise require heavy chemical input. This combination has long made them the crop of choice in regions too dry or too poor in soil quality to reliably support paddy or wheat.

The Nutritional Case

The renewed interest in millets rests heavily on their nutritional profile, which compares favorably with the polished rice and refined wheat that dominate the modern Indian diet. Millets are rich sources of dietary fiber, iron, calcium, and protein, and most are naturally gluten-free, making them suitable for individuals with celiac disease or gluten sensitivity. Their low glycaemic index means they release glucose into the bloodstream more slowly than rice or wheat, an important property for diabetics and for a country facing a rapidly rising burden of type-2 diabetes.

Different millets bring distinct nutritional strengths. Ragi (finger millet) is particularly prized for its high calcium content, making it a popular first food for infants and a recommended grain for pregnant and lactating women. Bajra (pearl millet) is a strong source of iron and is often promoted as part of anemia-control programs aimed at women and adolescent girls, a group in which India's anemia prevalence remains stubbornly high despite decades of nutrition interventions. Jowar (sorghum), meanwhile, offers a favorable balance of protein and slow-release carbohydrates, and has found renewed favor among urban consumers seeking wheat alternatives.

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Public health planners have taken note. Millets are being folded into flagship nutrition programs, including the Integrated Child Development Services (anganwadi meals), the Mid-Day Meal Scheme in schools, and, in select states, the Public Distribution System itself a recognition that dietary diversity, not just calorie sufficiency, is central to addressing India's persistent malnutrition and micronutrient deficiency burden.

Table 1: Major Millets and Their Nutritional Strengths

Millet	Key Nutritional Strength	Typical Growing Region
Jowar (Sorghum)	Balanced protein and slow-release carbohydrates	Maharashtra, Karnataka, Telangana
Bajra (Pearl millet)	Rich in iron; supports anaemia control	Rajasthan, Haryana, Gujarat
Ragi (Finger millet)	High in calcium; popular weaning food	Karnataka, Tamil Nadu, Uttarakhand
Foxtail millet	Good source of protein and fibre	Andhra Pradesh, Karnataka
Kodo millet	Low glycaemic index; suits diabetics	Madhya Pradesh, Chhattisgarh, tribal belts
Barnyard millet	Fast-growing; high fibre content	Uttarakhand, Tamil Nadu
Little millet	Rich in minerals; drought-tolerant	Odisha, Jharkhand, Madhya Pradesh

The Climate Resilience Case

If nutrition is one pillar of the millet revival, climate resilience is the other, and arguably the more urgent one. Millets require substantially less water than rice; commonly cited estimates suggest up to seventy percent less, making them far better suited to the rainfed, semi-arid, and drought-prone regions that cover a large share of India's cultivated area. As groundwater tables fall across northern and peninsular India and rainfall patterns grow more erratic under a changing climate, this water efficiency is not a marginal advantage; it may be a precondition for continued cultivation in many districts.

Millets also require minimal chemical fertilizer and pesticide input, reducing both cultivation costs and the environmental burden associated with intensive rice-wheat systems. Their short duration

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allows farmers greater flexibility in cropping calendars, letting them adjust sowing windows in years when the monsoon arrives late or withdraws early an increasingly common occurrence. For farmers in the driest tracts of Rajasthan, Maharashtra, Karnataka, and the tribal belts of central India, millets are not a lifestyle choice; they are often the only viable option when rainfall is scarce, and irrigation infrastructure is absent.

From Coarse Grain to Shree Anna: The Policy Turn

The government's engagement with millets has moved through distinct phases. Millets were long classified under the unflattering label of "coarse cereals" in official statistics, a term that itself reflected and reinforced their declining status. The turning point came with India's successful push at the United Nations, resulting in the UN General Assembly declaring 2023 as the International Year of Millets, a diplomatic and nutritional milestone that put Indian millets on the global stage.

Domestically, the Union Budget of 2023–24 renamed millets as "Shree Anna" and announced the Shree Anna Mission, a six-year initiative running through the Indian Institute of Millet Research to strengthen research, seed systems, processing infrastructure, and market linkages nationwide. States have layered their own schemes on top of this framework; Karnataka's long-running Ksheera Bhagya-linked millet meal programs and Odisha's Millets Mission, now rebranded as Shree Anna Abhiyan and operating across more than a hundred blocks in over thirty districts, are among the most established examples.

Financially, states can draw on the Rashtriya Krishi Vikas Yojana's Nutri-Cereals Sub-Mission to fund cluster demonstrations, quality seed distribution, water-use efficiency equipment, and post-harvest processing support for millet-growing farmers, with implementation left to each state's own priorities under the oversight of a State Level Sanctioning Committee.

Production Trends: A Cautious but Real Uptick

The numbers suggest the policy push is translating into measurable, if incremental, gains on the ground. India produced approximately 180 lakh tonnes of millets in 2024–25, a rise of over four lakh tonnes compared to the previous year, continuing a steady upward trend since the renewed policy attention began. India remains comfortably the world's largest millet producer, accounting for a large share of global output, according to FAO estimates.

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Rajasthan leads national production, reflecting the crop's deep agronomic fit with the state's arid conditions, followed by Maharashtra and Karnataka. This geographic concentration is itself instructive: millet cultivation continues to be strongest precisely where water scarcity leaves farmers with few better-yielding alternatives, underscoring both the opportunity and the challenge of the current moment. Production gains are real, but they remain concentrated in already-committed regions rather than spreading into new, wetter geographies where rice and wheat remain more profitable choices.

Building the Value Chain: Beyond the Farm Gate

A durable millet revival depends on more than higher production; it requires a functioning value chain that can process, package, and market these grains to a consumer base accustomed to polished rice and refined flour. This is where recent efforts have concentrated significant energy. Farmer Producer Organizations and women's self-help groups have emerged as key vehicles for small-scale millet processing, dehulling, milling, and converting raw grain into ready-to-cook and ready-to-eat products such as flours, flakes, and snacks.

One widely cited example comes from Bhadrachalam in Telangana, where women who once worked as agricultural laborers now run a millet-based biscuit and snack enterprise, illustrating how processing and branding can convert a low-value commodity into a higher-margin product while creating rural, women-led livelihoods. Government-backed millet fairs, buyer-seller meets, and a Global Millets Conference bringing together international scientists, nutritionists, and startup leaders have similarly tried to build the market linkages and export potential that a purely production-focused push would miss.

Private food companies have also begun mainstreaming millets into urban retail; millet-based breakfast cereals, energy bars, and bakery products now sit on supermarket shelves that a decade ago carried none. Whether this urban demand is deep enough to absorb sustained production growth, or remains a premium niche, will be one of the defining questions of the next several years.

The Barriers that Remain

Despite the policy momentum, the millet revival faces real structural constraints. Processing remains the single biggest bottleneck: unlike rice and wheat, which benefit from decades of mechanized milling infrastructure, millets, particularly the hard-husked minor millets, require specialized dehulling

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equipment that remains scarce and expensive at the village level, limiting how much raw grain can be converted into consumer-ready products locally.

Yields, while improving with better varieties, still lag behind rice and wheat in absolute terms, and minimum support price mechanisms for millets have historically been less robust and less consistently implemented than those for paddy and wheat, leaving farmers exposed to price volatility even when procurement policies exist on paper. Consumer habits present a further challenge: taste, cooking time, and unfamiliarity with preparation methods continue to limit millet uptake in urban middle-class kitchens, despite growing health consciousness, and reversing decades of dietary preference for polished grains will take sustained consumer education rather than a single policy cycle.

The Role of Extension and Research Systems

As with most agricultural transitions in India, the success of the millet push will depend heavily on the reach and credibility of extension systems working directly with farmers. Krishi Vigyan Kendras and State Agricultural Universities have a central role to play in demonstrating improved millet varieties, training farmers in efficient sowing and harvesting techniques, and connecting growers with Farmer Producer Organizations that can aggregate produce for processing and sale.

The Indian Institute of Millet Research, anchoring the Shree Anna Mission, is positioned to serve a similar function at the research level, developing higher-yielding, more pest-resistant varieties and simplified processing technologies suited to smallholder conditions. ATMA functionaries, meanwhile, remain crucial for the last-mile work of building farmer confidence: convincing a rainfed farmer to shift acreage back toward a crop their own parents may have abandoned a generation ago requires more than policy announcements; it requires visible, local proof that markets and prices will reward the switch.

A Global Grain, Not Just an Indian One

India's millet push has also had a notable diplomatic dimension. By leading the successful UN resolution for the International Year of Millets and hosting global conferences that bring together agriculture ministers, scientists, and industry leaders from multiple countries, India has positioned itself as an advocate for millets as a global solution to food security challenges particularly for regions of the Global South facing both water stress and malnutrition, even as parts of the Global North grapple with diet-related chronic disease.

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This global framing matters for India's own millet economy too: export potential, international scientific collaboration, and cross-country learning on processing technology and market development all stand to benefit from India's willingness to position millets as shared global heritage rather than a purely domestic revival project.

What Farmers Still Need to Hear

Behind every production statistic is an individual farmer weighing whether to allocate scarce land and labour to millets rather than a more familiar, better-supported crop. For many, that decision still comes down to two practical questions: will there be a buyer at a fair price when the crop is ready, and will the effort of growing an unfamiliar or long-abandoned grain be worth it compared to the guaranteed procurement systems built around paddy and wheat over decades?

This is where the gap between announced policy and lived farmer experience remains widest. Minimum support price coverage for millets exists on paper in most states, but procurement infrastructure, designated purchase centers, timely payment systems, and storage capacity are nowhere near as extensive or dependable as what has been built for rice and wheat over the Green Revolution era. Farmers who have seen government promises around minor crops fade in previous decades are, understandably, cautious about committing land to millets purely on the strength of a new scheme, however well-funded. Sustained, visible follow-through, not just at the mission-launch stage but season after season, will be what ultimately convinces skeptical farmers to make the shift durable rather than temporary.

Conclusion

Millets sit at a genuinely rare intersection of public health need, climate adaptation, and farmer welfare, three policy goals that do not always align so neatly around a single crop. The production numbers, institutional architecture, and international recognition built up since 2023 represent real, tangible progress rather than mere sloganeering. But a lasting revolution will require more than favorable statistics from the driest, already-committed millet belts of Rajasthan, Karnataka, and Maharashtra.

It will require processing infrastructure that reaches the village level, procurement mechanisms as reliable as those for rice and wheat, consumer education that changes what appears on urban dinner plates by habit rather than only during health-conscious phases, and extension systems capable of convincing farmers in wetter, more fertile regions that millets are worth a share of their land too. If

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these pieces come together, Shree Anna may yet fulfill its promise, not as a nostalgic footnote to the Green Revolution, but as a genuine second chapter in India's food security story.

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The Internet of Things (IoT) in Agriculture: Connected Farms for Better Productivity

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Abstract

The Internet of Things (IoT) is turning ordinary farms into connected, data-driven enterprises. By linking together sensors, machines, and mobile phones, IoT allows a field to continuously report its own condition soil moisture, temperature, crop health, and more and even to act on that information automatically. This article explains, in accessible terms, what IoT is and how a connected farm works through its four layers of sensing, connectivity, processing, and action. It surveys the main applications transforming Indian agriculture, including smart irrigation, precision nutrient delivery, livestock and greenhouse monitoring, storage and cold-chain tracking, and farm security, and it demystifies the wireless technologies, such as low-power long-range networks, that make them possible on scattered rural fields. Weighing clear benefits- water and input savings, higher and steadier yields, and reduced labour against real challenges of cost, connectivity, and digital literacy, and drawing on documented deployments and supportive national programmes, it argues that IoT, adapted to India's smallholder context through shared and affordable models, can meaningfully raise farm productivity and resilience.

Keywords: *Internet of Things, connected farms, smart agriculture, sensors, smart irrigation, precision farming, digital agriculture, farm productivity.*

1. Introduction

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Imagine a farm that can talk. The soil sends a message when it grows thirsty; the water pump switches itself on and off in reply. A weather station warns of an approaching cold night; a greenhouse quietly adjusts to protect the crop. A cattle shed alerts the farmer's phone the moment an animal falls sick. This is not science fiction it is the Internet of Things at work, and it is steadily arriving on Indian farms. Where earlier technologies gave the farmer isolated tools, the Internet of Things links those tools into a single, connected system that senses, communicates, and acts.

The idea is powerful precisely because farming is so exposed to conditions the farmer cannot see or be everywhere to watch. Soil moisture varies from corner to corner; pests appear overnight; storage sheds spoil produce in silence. A connected farm keeps watch around the clock, gathers information from every part of the operation, and delivers it to the farmer's hand or acts on it directly. The promise is a farm that wastes less, produces more, and demands less constant physical presence. This article explains how IoT works in agriculture, what it can do, and how it is helping raise productivity on Indian farms.

2.1 What Is the Internet of Things?

The Internet of Things is, at heart, a simple idea: everyday objects fitted with small sensors and a connection to the internet, so that they can collect information, share it, and sometimes act on it all with little or no human effort. A fitness band that counts your steps and sends them to your phone is an example of IoT. On a farm, the 'things' are soil probes, weather stations, water pumps, cameras, and livestock tags. Once connected, they stop being separate gadgets and become a coordinated network in which data flows freely and decisions can be made in real time. In short, IoT gives the farm a sense of awareness it never had before.

2.2 How a Connected Farm Works

A connected farm can be understood as four layers working together, each passing information to the next. Sensors gather the raw facts; a network carries them; software makes sense of them; and machines act on the conclusion. Understanding these layers makes the whole system far less mysterious

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Layer	What It Does on the Farm
1. Sensing layer	Sensors measure soil moisture, temperature, humidity, crop health, and animal condition
2. Connectivity layer	Wireless networks carry the data from the field to the farmer or the cloud
3. Processing layer	Software and AI turn raw data into clear alerts and recommendations
4. Action layer	Pumps, valves, and machines act — automatically or on the farmer's command

The magic lies in the loop these layers form. A soil sensor notices dryness, the network reports it, the software decides irrigation is needed, and a valve opens to deliver exactly the right amount of water then closes again. The farmer may simply receive a message on the phone confirming what was done. This continuous cycle of sense, communicate, decide, and act is what separates a truly connected farm from a collection of standalone devices.

2.3 Key Applications on the Connected Farm

IoT is not a single product but a toolkit, and its uses on the farm are many:

- **Smart irrigation:** Soil-moisture sensors and weather data drive automatic drip and sprinkler systems, delivering water only when and where the crop needs it and cutting waste dramatically.
- **Precision nutrition and fertigation**: Connected systems dose fertilizer through the irrigation water in exact amounts, matching supply to the crop's real-time demand.
- **Livestock monitoring**: Wearable tags and shed sensors track an animal's health, movement, and body temperature, flagging illness or the right time for breeding early.
- **Greenhouse and polyhouse automation**: Sensors and controllers hold temperature, humidity, and light at ideal levels, protecting high-value crops from weather swings.
- **Storage and cold-chain monitoring:** Sensors watch temperature and humidity in warehouses and cold stores, warning of conditions that would spoil grain, fruit, or vegetables.

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- **Farm security:** Cameras and motion sensors guard fields and equipment against theft and stray animals, alerting the farmer instantly.

2.4 Talking Across the Field: Connectivity Made Simple

For devices to cooperate, they must be able to communicate, and farms pose a special challenge: fields are large, scattered, and often far from strong internet or mobile signals. Several wireless technologies solve this in different ways. Ordinary Wi-Fi works well within a small area such as a greenhouse or farmyard. Mobile networks carry data wherever there is cellular coverage. For large or remote fields, low-power, long-range technologies able to send small packets of sensor data over many kilometers on a tiny battery are especially valuable, because they keep both cost and power use very low. Choosing the right kind of connectivity for the local conditions is the key to a reliable connected farm.

2.5 Benefits of the Connected Farm

Benefit	**How It Helps the Farmer and the Land**
Water and input savings	Automatic, need-based irrigation and fertiliser cut waste and cost
Higher, steadier yields	Ideal, constantly maintained conditions raise and stabilise output
Reduced labour and effort	Automation handles routine tasks and constant monitoring
Early warnings	Alerts on pests, disease, weather, and spoilage prevent big losses
Remote management	The farmer can monitor and control the farm from a phone, anywhere
Less post-harvest loss	Storage monitoring protects produce until it reaches the market

2.6 Challenges to Adoption

The connected farm faces genuine obstacles in India. The most fundamental is the small and fragmented nature of most holdings, which makes it hard for an individual farmer to justify the cost of sensors, controllers, and connectivity, pointing again to shared and cooperative models as the practical way forward. Patchy internet and unreliable electricity in rural areas can break the very connections IoT depends on, though low-power networks and solar power help. Other hurdles include the upfront expense of devices, limited digital skills, the difficulty of getting equipment from different makers to work together, and important concerns about the security and privacy of farm data. Affordable kits, local-language interfaces, reliable rural connectivity, and simple training are all needed to bring the connected farm within reach of the ordinary cultivator.

3. Case Studies: Farms That Got Connected

IoT is already moving from demonstration to deployment across Indian agriculture.

3.1 A Large-Scale Smart-Agriculture Pilot

In a major connected-agriculture project in India, telecom and technology partners installed hundreds of sensors across tens of thousands of hectares, aiming to benefit around fifty thousand farmers. The system combined smart irrigation, pest control, and weather and crop advisories delivered in local languages, showing how a shared IoT platform can extend the benefits of connected farming to large numbers of smallholders at once.

3.2 Smart Drip Irrigation Kits

Affordable smart-irrigation kits a soil-moisture sensor, a low-cost controller, and a valve linked to a mobile app, now let farmers automate watering on individual plots. Farmers using them report noticeable water and power savings and healthier crops, because water is applied precisely to need rather than by routine, and the system can be checked or adjusted from a phone.

3.3 Polyhouse and Greenhouse Automation

Growers of high-value vegetables and flowers in protected structures increasingly rely on IoT controllers to maintain ideal temperature, humidity, and irrigation automatically. By holding the growing environment steady around the clock, these systems raise quality and yield while reducing the constant manual attention such crops would otherwise demand.

3.4 Gram-Panchayat Weather Networks

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Government-supported networks of automated weather stations are being established at the village level to provide hyper-local weather information. Because a district forecast may miss what is happening in a particular village, these local stations give farmers far more accurate guidance on when to sow, irrigate, spray, or harvest a foundational layer of data for every other connected application.

4. Policy Support and Government Initiatives

Government programmes are building the digital foundation on which connected farming depends.

- **Digital Agriculture Mission**: Creates the digital public infrastructure, including a farmer registry and a satellite-linked decision support system that connected services can build upon.
- **Weather station networks**: Central initiatives are expanding automated, village-level weather data systems to deliver localized advisories to farmers.
- **Micro-irrigation support under PMKSY**: Promotes drip and sprinkler systems that form the backbone for smart, sensor-driven irrigation, with IoT components increasingly eligible for support.
- **Mechanization and custom hiring centers (SMAM):** Encourage shared access to advanced equipment, a model well suited to spreading IoT among small farmers.
- **Krishi Vigyan Kendras and ICAR**: Demonstrate connected technologies and train farmers to use and maintain them.

5. Key Takeaways

- The Internet of Things links sensors, machines, and phones so a farm can sense, communicate, and act on its own.
- A connected farm works through four layers: sensing, connectivity, processing, and action.
- Major applications include smart irrigation, fertigation, livestock and greenhouse monitoring, storage tracking, and farm security.
- Low-power, long-range wireless networks make IoT workable on large and remote fields.
- Benefits include input and water savings, higher and steadier yields, early warnings, and remote management.
- For India's small farms, affordable kits and shared models are the key to adoption.

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- Start small with one high-value problem, prove the savings, and expand step by step.

6. Conclusion

Agriculture has always depended on the farmer's ability to observe and respond, to read the soil, the sky, and the crop, and to act in time. The Internet of Things extends that ability far beyond what any single pair of hands and eyes can manage. It lets the field itself keep watch, report what it finds, and act on the farmer's behalf, turning a scattered set of tasks into a smoothly coordinated, connected whole.

For India, with its millions of small farms and its pressing need to grow more from less, the potential is enormous. A connected farm uses water and inputs precisely, warns of trouble before it strikes, guards against loss, and frees the farmer from constant physical presence all of which translate into higher productivity and steadier incomes. The path forward lies in making these technologies affordable, connecting rural areas reliably, sharing costly equipment through cooperatives and hiring centres, and teaching farmers to use them with confidence. If that is done, the connected farm need not remain the privilege of the few. The day when an ordinary farmer's field can quietly report its needs, and be answered, is no longer distant and with it comes the promise of a more productive, efficient, and resilient Indian agriculture.

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AI, Drones and Sensors: The Future of Precision Farming in India

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Abstract

Indian agriculture stands at the edge of a digital transformation. Artificial intelligence, drones, and sensors are moving out of laboratories and into farmers' fields, promising a shift from broad, one-size-fits-all practices toward precision farming, applying the right input, in the right amount, at the right place and time. This article explains what precision farming is and how its three core technologies work in the Indian context. Artificial intelligence powers crop advisories, pest and disease detection, yield and price forecasting, and multilingual farmer chatbots; drones spray crops, monitor plant health, and map fields far faster than manual methods; and soil, weather, and satellite sensors feed a continuous stream of data that guides decisions. It describes how these tools work together in a data-to-decision loop, weighs their benefits against real challenges such as small landholdings, cost, and digital literacy, and reviews major government initiatives including the Digital Agriculture Mission, AgriStack, the Namo Drone Didi scheme, and AI-based pest surveillance. It concludes that, adapted to India's smallholder reality through shared-service models, these technologies can make farming more productive, profitable, and sustainable.

Keywords: *precision farming, artificial intelligence, agricultural drones, sensors, Internet of Things, digital agriculture, AgriStack, smart farming.*

1. Introduction

For most of history, farming has been an art of averages. A farmer treated an entire field as a single unit, the same seed rate, the same fertilizer dose, the same spray schedule across every corner

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of the land, whether that corner was rich or poor, wet or dry. This blanket approach wastes inputs where they are not needed and starves the crop where more would help. In a country like India, where land, water, and money are all under pressure and most farmers work small plots, that waste is costly.

A new generation of technology is changing this picture. Artificial intelligence can read a photograph of a leaf and name the disease attacking it. Drones can fly over a field and spray it in minutes, or map exactly which patches are stressed. Sensors buried in the soil and mounted on satellites can report moisture, nutrients, and crop health in real time. Together, these tools make possible a smarter kind of agriculture, precision farming in which decisions are guided by data rather than habit. Once the preserve of large mechanized farms abroad, these technologies are now reaching Indian villages, carried by falling costs, better connectivity, and a wave of supportive government schemes. This article explains how AI, drones, and sensors work on the farm, and what they mean for the future of Indian agriculture

❖ A drone can spray three to four hectares of crop in a day, compared with roughly half a hectare by a person with a knapsack sprayer, while keeping the operator away from harmful chemicals and using far less water

2.1 What Is Precision Farming?

Precision farming, also called smart farming, is the practice of managing a field not as one uniform block but as many small zones, each treated according to its specific needs. Its guiding principle is to deliver the right input, seed, water, fertilizer, or pesticide in the right amount, at the right place, and at the right time. To do this, a farmer needs information: what the soil holds, how the crop is growing, where pests are appearing, and what the weather will do. AI, drones, and sensors are the tools that gather this information, make sense of it, and help act on it. The result is less waste, lower cost, higher yield, and reduced harm to the environment.

2.2 Artificial Intelligence in the Field

Artificial intelligence is the 'brain' of precision farming. By learning from vast amounts of data, images, weather records, soil tests, and past yields, AI systems can spot patterns and make predictions that would take a human expert far longer to reach. In Indian agriculture, AI is already at work in several ways. It powers crop advisory services that tell farmers when to sow, irrigate, or

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spray. It detects pests and diseases from photographs, flagging trouble before it spreads. It forecasts yields and market prices, helping farmers plan and bargain. And it answers farmers' questions directly: AI-powered chatbots now respond to thousands of queries a day in many regional languages, putting expert guidance within reach of anyone with a phone. National systems for AI-based pest surveillance and satellite-linked decision support are extending this intelligence to millions of farmers at once.

Expert Advice

AI does not replace the farmer's judgment; it sharpens it. Treat an AI advisory as a well-informed second opinion: combine it with your own knowledge of the field, and you will make better decisions than either could alone.

2.3 Drones on the Farm

If AI is the brain, drones are the tireless hands and eyes that operate above the crop. Their most visible use in India is spraying, applying liquid fertilizers, pesticides, and nano-fertilizers quickly, evenly, and safely, covering in minutes what would take hours by hand. But drones do much more than spray. Fitted with ordinary and multispectral cameras, they scan fields to reveal crop health invisible to the naked eye, pinpointing patches suffering from water stress, nutrient deficiency, or pest attack so that treatment can be targeted precisely. They map fields and land parcels, monitor large areas rapidly, and assess crop damage after floods, storms, or droughts for quick and fair insurance settlement. By reducing chemical use, protecting operators from exposure, and saving labour and time, drones are becoming one of the most practical entry points into precision farming for Indian farmers.

2.4 Sensors and the Internet of Things

Sensors are the nervous system of the smart farm, constantly sensing conditions and sending back data. Soil sensors measure moisture, temperature, and nutrient levels, telling a farmer exactly when and how much to irrigate or fertilize rather than guessing. Weather stations placed close to the field give localized forecasts far more useful than a district-wide bulletin. Handheld and tractor-mounted crop sensors read the greenness and vigor of plants to guide precise, need-based nitrogen application. Above it all, satellite remote sensing watches entire regions, tracking crop growth, drought,

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and acreage. When these devices are connected together, the Internet of Things, or IoT, forms a web of information that can even trigger action automatically, such as switching on drip irrigation when the soil turns dry.

Technology	What It Does on the Farm
Artificial Intelligence	Crop advice, pest and disease detection, yield and price prediction, chatbots
Spraying & scouting drones	Fast, safe spraying; crop-health mapping; field mapping; damage assessment
Soil sensors	Measure moisture, temperature and nutrients for need-based irrigation and fertiliser
Weather stations	Provide localised forecasts for timely field decisions
Crop / canopy sensors	Read plant vigour to guide precise nitrogen application
Satellite remote sensing	Monitor crop growth, drought and acreage across large areas

2.5 How they Work Together

The real power of these technologies lies not in any one of them, but in how they connect. Sensors and satellites gather the raw data; artificial intelligence turns that data into a clear recommendation; and drones or machinery carry out the action in the field. This 'sense–think–act' loop repeats through the season, learning and improving each time. A soil sensor detects dryness, AI decides how much water the crop needs, and an irrigation system delivers exactly that, no more, no less. A satellite spots a stressed patch, AI diagnoses the likely cause, and a drone sprays only that patch. This coordinated intelligence is what transforms scattered gadgets into genuine precision farming.

2.6 Benefits of Precision Farming

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Benefit	How It Helps the Farmer and the Land
Lower input costs	Seed, water, fertiliser and pesticide used only where needed
Higher yields	Timely, targeted care lets crops reach their full potential
Time and labour savings	Drones and automation cover more ground with less effort
Safer, cleaner farming	Less chemical exposure and reduced runoff into soil and water
Better decisions	Real-time data and AI advice reduce guesswork and risk
New rural livelihoods	Drone piloting and digital services create village-level jobs

2.7 Challenges to Adoption

For all their promise, these technologies face real hurdles in India. The biggest is the structure of farming itself: the overwhelming majority of Indian farmers are small and marginal, working tiny, scattered plots on which costly drones, sensors, and machinery are hard to justify individually. The answer lies in shared-service and rental models, custom hiring centres and women-led drone groups that let many farmers benefit from equipment none of them owns alone. Other challenges include the upfront cost of technology, gaps in digital literacy, patchy internet and electricity in rural areas, incomplete land records that make it hard to link farmers to digital services, and legitimate concerns about data privacy. Overcoming these requires affordable access, patient training, reliable connectivity, and careful safeguards, so that the digital revolution reaches the smallholder, not only the large farmer.

3. Case Studies: Technology Reaching the Field

Across India, AI, drones, and sensors are already moving from pilot projects to everyday tools.

3.1 Women as Drone Entrepreneurs

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Under the Namo Drone Didi scheme, women's self-help groups are being equipped with agricultural drones and trained to fly them, offering spraying services to local farmers on rent. This turns a costly technology into an affordable, pay-per-use service, spreads precision spraying to smallholders, and creates a new and dignified source of income for rural women, a striking example of technology and social empowerment advancing together.

3.2 AI-Based Pest Surveillance

A national AI-powered pest surveillance system now helps detect infestations early across a wide range of crops and pests. Extension workers and farmers can identify problems from images and receive timely warnings, allowing targeted action before a local outbreak becomes a regional disaster. By linking farmers to scientific expertise in real time, it turns pest management from reactive to preventive.

3.3 AI Chatbots and Local Forecasts

Voice-enabled AI chatbots answer farmers' questions about schemes and practices in many regional languages, handling thousands of queries every day. In parallel, AI-based local monsoon-onset forecasts have been piloted with the meteorological department and delivered by text message to millions of farmers, with surveys showing that a substantial share adjusted their sowing and land-preparation decisions accordingly, evidence that timely, localized AI advice genuinely changes behavior in the field.

4. Policy Support and Government Initiatives

A strong policy push is driving the spread of digital and precision agriculture in India.

- **Digital Agriculture Mission**: An umbrella mission building the digital backbone of Indian farming, including AgriStack, a farmer registry with unique digital Farmer IDs linked to land and crop data and a satellite-based decision support system.
- **Namo Drone Didi Scheme**: A central scheme providing drones to thousands of women-led self-help groups, with a large subsidy, to offer drone-spraying services to farmers.
- **Sub-Mission on Agricultural Mechanization (SMAM)**: Offers subsidies to farmers and custom hiring centres for purchasing agricultural drones and equipment.

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- **Drone Rules, 2021**: A simplified regulatory framework that made it far easier to operate drones for spraying, mapping, and monitoring.

- **AI-based systems:** National pest surveillance, AI crop advisories, and multilingual farmer chatbots extend expert guidance to millions of farmers.
- **Krishi Vigyan Kendras and ICAR**: Demonstrate precision technologies and train farmers in their use on the ground.

5. Key Takeaways

- Precision farming means the right input, in the right amount, at the right place and time guided by data, not habit.
- Artificial intelligence provides advice, pest and disease detection, forecasting, and chatbots in local languages.
- Drones spray crops quickly and safely and map crop health that the eye cannot see.
- Soil, weather, crop, and satellite sensors feed real-time data that guides every decision.
- The technologies are most powerful when linked in a sense–think–act loop.
- For India's small farms, shared-service and rental models are the key to affordable access.
- Government schemes, Digital Agriculture Mission, AgriStack, Namo Drone Didi, SMAM, and Drone Rules 2021, are accelerating adoption.

6. Conclusion

Indian agriculture is being quietly rewired. The farmer who once relied only on inherited wisdom and a watchful eye now has, within reach, a set of tools that can see further, calculate faster, and act more precisely than ever before. Artificial intelligence brings expert knowledge to the humblest smartphone; drones bring speed, safety, and reach to spraying and scouting; and sensors turn the invisible state of soil and crop into information a farmer can use.

The future of precision farming in India will not look like the vast, machine-run farms of other countries. It will be shaped by India's own reality of small holdings and shared resources, drones flown by village women's groups, sensors serving whole clusters of farms, and AI advice delivered in a farmer's mother tongue. If these technologies are made affordable, accessible, and easy to use, and if farmers are trained and trusted to use them, they can raise incomes, conserve scarce resources, and

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build resilience against a changing climate. The goal is not technology for its own sake, but a farmer who, armed with better information, makes better decisions and a farm that thinks before it acts. That is the promise, and increasingly the reality, of precision farming in India.

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REGENERATIVE AGRICULTURE: *Restoring Soil Health for Future Generations*

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Abstract

Decades of intensive tillage, monocropping, and heavy agrochemical use have left large parts of the world's farmland with depleted organic matter, weakened structure, and declining long-term productivity. Regenerative agriculture has emerged as a response, not a single technique, but a set of principles aimed at actively rebuilding soil health rather than merely sustaining it at its current, often degraded, state. This article examines the core principles of regenerative agriculture, including minimal soil disturbance, continuous living cover, crop diversity, and integrated livestock, and distinguishes the approach from related movements such as organic and natural farming. It reviews the evidence linking regenerative practices to improved soil carbon, water infiltration, and farm resilience, profiles Indian and global examples of the approach in practice, and considers the economic and institutional barriers that stand between regenerative agriculture's promise and its adoption at meaningful scale.

Introduction

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There is a quiet but important shift underway in how agricultural scientists and farmers talk about soil. For much of the last century, soil was treated largely as a medium something to hold a crop upright while nutrients were supplied from a bag. Regenerative agriculture asks a different question: what would farming look like if the primary goal, each season, was to leave the soil measurably healthier than it was found? That single reframing, simple as it sounds, changes almost every decision a farmer makes, from how the land is tilled to what grows on it between cash crops to whether livestock ever set foot on the field at all.

- The term 'regenerative agriculture' was popularized in the 1980s by the Rodale Institute, building on earlier organic farming research.
- Healthy agricultural soils can hold significant amounts of carbon, making soil carbon sequestration a central regenerative agriculture goal.
- Regenerative agriculture is defined by outcomes, improving soil health over time, rather than by a fixed checklist of permitted or banned inputs.
- Estimates suggest a large share of the world's agricultural soils have lost a substantial portion of their original organic carbon content since the onset of intensive cultivation.

What Makes Agriculture 'Regenerative'?

Unlike organic or natural farming, which are defined largely by which inputs are permitted or excluded, regenerative agriculture is defined by outcome: is the soil's biological, physical, and chemical health improving over successive seasons? This outcome-based framing means a regenerative farm could, in principle, use some synthetic inputs during a transition period, provided the overall trajectory of soil health is upward, though in practice, most regenerative systems minimize synthetic inputs substantially as soil biology strengthens and reduces the need for them.

This distinction matters because it shifts the conversation from ideology to measurement. A regenerative farmer is less concerned with whether a particular input is labeled organic or natural, and more concerned with tracking indicators such as soil organic matter, water infiltration rate, earthworm counts, and root depth, concrete signs that the underlying soil ecosystem is becoming more resilient and self-sustaining season after season.

The Five Core Principles

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While practitioners and researchers frame the details somewhat differently, most descriptions of regenerative agriculture converge on a similar set of guiding principles, each reinforcing the others rather than functioning as a standalone checklist item.

Principle	What it Involves	Why it Matters
Minimise soil disturbance	Reduced or zero tillage	Protects soil structure and fungal networks
Keep soil covered	Cover crops, mulching, crop residue retention	Prevents erosion and moderates soil temperature
Maintain living roots	Continuous cropping or cover cropping year-round	Feeds soil microbiology through root exudates
Maximise diversity	Crop rotation, intercropping, polycultures	Builds pest resilience and balanced nutrient cycling
Integrate livestock	Managed grazing, crop-livestock integration	Cycles nutrients and stimulates plant regrowth

How Regenerative Agriculture Differs from Related Movements

Farmers and researchers alike sometimes lump regenerative agriculture together with organic or natural farming, but the relationship is better understood as overlapping rather than identical. Organic farming's defining feature is certification against a fixed list of permitted and prohibited inputs; a field can be certified organic while still being intensively tilled and planted in continuous monoculture, practices that would work against regenerative goals even if every input used were organic-approved. Natural farming, similarly, focuses on minimizing external inputs and activating native soil biology through specific preparations, but does not itself mandate crop diversity or livestock integration in the way regenerative frameworks typically emphasize.

Regenerative agriculture can, in practice, be layered on top of either system a farm can be simultaneously organic-certified and regenerative, or practicing natural farming principles while also actively pursuing the five regenerative principles above. What regenerative agriculture adds is a

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sharper, more measurable focus specifically on soil health trajectory as the central success metric, rather than input use as the primary criterion.

What the Science Says About Soil Carbon and Resilience?

The evidence base for regenerative practices is strongest at the level of individual mechanisms, even where whole-system, long-term data remains comparatively limited. Reduced tillage has been shown repeatedly to preserve soil aggregate structure and fungal hyphal networks that intensive tillage disrupts. Cover cropping measurably increases soil organic carbon over multi-year periods in a wide range of climates, while also improving water infiltration a benefit that becomes increasingly valuable as rainfall grows more erratic under a changing climate. Diverse crop rotations have consistently been linked to reduced pest and disease pressure, lowering the need for chemical intervention over time.

The evidence is thinner on quantifying exactly how much carbon regenerative systems can sequester at scale, and for how long that carbon remains stable in the soil rather than being released again through subsequent disturbance. Soil carbon sequestration rates vary widely by climate, soil type, and specific management combination, which makes broad claims about regenerative agriculture's climate mitigation potential harder to verify uniformly than claims about its soil health and resilience benefits, which rest on a considerably more consistent body of research.

DID YOU KNOW?

- A single teaspoon of healthy agricultural soil can contain billions of microorganisms, most of them still unidentified by science.
- Cover crop roots can extend the period of active photosynthesis and root exudation well beyond the main cropping season, feeding soil microbes even when no cash crop is in the field.
- Managed rotational grazing, a core regenerative livestock practice, mimics the grazing and rest patterns of wild herbivore herds that historically shaped grassland soil health.

The Economics of Transition

Farmers considering a shift toward regenerative practices face a financial arithmetic that differs meaningfully from both conventional and organic transitions. Reduced tillage and cover cropping typically lower fuel and labor costs associated with field preparation over time, and diminished reliance on synthetic fertilizer as soil biology strengthens can meaningfully cut input spending within a few years. But the transition period itself often requires upfront investment: cover crop seed, possibly new no-till planting equipment, and the time needed to learn a more complex, biologically driven system of management decisions rather than a fixed input schedule.

Livestock integration adds a further layer of economic complexity and opportunity. Managed grazing on cover crops or crop residue can generate additional income streams from meat, milk, or wool, while simultaneously returning nutrients to the soil through manure, effectively turning what would otherwise be a pure cost center into a second revenue-generating enterprise on the same land. Farms that successfully integrate livestock into a regenerative cropping system often report that this diversification, more than any single soil health metric, is what makes the economics work during the multi-year transition period.

Because regenerative agriculture lacks the standardized certification and price premium infrastructure that organic farming has built over decades, most of the current financial case rests on cost reduction and risk mitigation rather than market premium. A regenerative field with better water infiltration and deeper root systems tends to weather a dry spell or a heavy rainfall event with less yield loss than a comparable conventionally managed field, a resilience benefit that may not show up in an average year's balance sheet but becomes decisive in the increasingly frequent extreme years that a changing climate is producing.

Tracking Progress: Indicators Farmers Can Monitor

Because regenerative agriculture is defined by trajectory rather than a fixed checklist, farmers and extension workers need practical ways to track whether soil health is actually improving season over season. Several indicators have proven both scientifically meaningful and accessible enough for farmers to monitor without expensive laboratory equipment, alongside laboratory-based measures that provide a more rigorous baseline where testing infrastructure is available.

- ✓ Soil organic matter percentage, tracked through periodic laboratory testing
- ✓ Water infiltration rate, measurable with a simple ring infiltrometer test in the field
- ✓ Earthworm counts per spadeful of soil, a widely used proxy for biological activity

- ✓ Soil aggregate stability, assessed through simple slake tests comparing how soil clumps hold together in water
- ✓ Root depth and density of the current crop, observed through soil pit inspection

None of these indicators alone tells the full story, but tracked together over several seasons they give farmers and advisors a grounded, evidence-based picture of whether a farm's regenerative transition is actually working, replacing guesswork and anecdote with the kind of concrete feedback that sustains confidence through the inevitably uneven early years of transition.

Regenerative Agriculture in Practice: Two Examples

Madhya Pradesh: Rebuilding Degraded Rainfed Land

In parts of rainfed Madhya Pradesh, watershed-based regenerative interventions combining contour bunding, cover cropping, and reduced tillage have been used to rehabilitate land that had become increasingly unproductive after decades of continuous cotton and soybean monocropping. Farmers adopting multi-crop rotations alongside these physical soil-and-water conservation measures have reported steadier yields through dry spells compared to neighboring fields under conventional continuous cropping, illustrating how regenerative principles can be layered onto existing watershed development infrastructure rather than requiring an entirely separate program.

The U.S. Northern Plains: Farmer-Led Innovation

Some of the most closely studied regenerative agriculture examples globally come from farmer-led no-till and cover-cropping networks in the northern United States, where growers facing severe wind erosion and declining soil organic matter began experimenting with diverse multi-species cover crop mixes and integrated cattle grazing decades before regenerative agriculture became a widely used term. Long-term data from these farms, some spanning over twenty years of continuous practice, show measurable increases in soil organic matter and water infiltration capacity, offering some of the clearest longitudinal evidence available for regenerative agriculture's soil health claims.

Andhra Pradesh: Convergence with Natural Farming

Several natural farming programmes in India, including large-scale initiatives in Andhra Pradesh, have increasingly incorporated explicitly regenerative elements alongside their original zero-input philosophy, multi-species cover cropping, structured crop rotation planning, and deliberate integration of farm animals beyond just their role as a source of Jivamrita inputs. This convergence illustrates a broader pattern: rather than remaining a separate, competing movement, regenerative principles are increasingly being layered onto existing natural and organic farming programmes as a way of sharpening their focus on measurable soil outcomes.

Policy and Institutional Landscape

Regenerative agriculture does not yet have a dedicated, unified national scheme in India comparable to the Paramparagat Krishi Vikas Yojana for organic farming or the Bharatiya Prakritik Krishi Paddhati for natural farming, though several existing programmes overlap substantially with regenerative goals. Watershed development schemes, soil health card initiatives, and agroforestry promotion programs all support practices- contour management, nutrient monitoring, tree integration- that align closely with regenerative principles even where the term itself is not used in the scheme's name.

Globally, interest is moving faster on the policy front. Several national governments and multilateral development banks have begun piloting outcome-based payment programmes that compensate farmers directly for measured soil carbon gains or verified improvements in soil health indicators, rather than for adopting a specific prescribed practice. If these outcome-based models mature and prove administratively workable at scale, they could offer exactly the kind of price signal that regenerative agriculture currently lacks, rewarding farmers for the soil health trajectory itself rather than for following a fixed input or certification checklist, which fits naturally with how the approach is already defined.

Barriers to Wider Adoption

Despite growing interest, regenerative agriculture faces adoption barriers that are less about farmer conviction and more about structural constraints. Transitioning away from tillage and toward diverse rotations often requires new equipment, new knowledge, and a tolerance for short-term yield variability while soil biology rebuilds, a transition period that can be financially difficult for farmers operating on thin margins or without access to credit designed for this kind of multi-year investment. Markets, too, rarely reward regenerative practices directly the way certified organic markets reward organic certification; without a clear price premium or verified carbon credit mechanism, the financial case for transition rests largely on long-term cost savings and resilience benefits that are harder to see in a single season's balance sheet.

- Equipment and knowledge gaps for reduced-tillage and cover-cropping systems
- Short-term yield variability during the multi-year soil-rebuilding transition
- Absence of standardized certification or price premium comparable to organic markets
- Limited access to credit products structured around multi-year transition timelines
- Thin, still-developing scientific consensus on carbon sequestration rates across diverse soil types

The Way Forward

Scaling regenerative agriculture will likely depend less on any single breakthrough technology and more on aligning the institutions around farmers, credit providers, extension services, and markets with the multi-year timeline that genuine soil regeneration requires. Extension education has a distinct role here: helping farmers set realistic expectations for the transition period, connecting them with peer farmers who have already made the shift, and providing the soil-testing and monitoring support needed to track progress against concrete indicators rather than anecdote alone.

Emerging carbon credit markets and corporate sustainability sourcing programmes are beginning to offer some farmers direct financial incentives tied to measured soil carbon gains, though verification methodologies remain young and are still being refined. Public research investment in region-specific regenerative practice guidance, since what works on a Madhya Pradesh rainfed farm will differ meaningfully from what works on an irrigated Punjab plot, will be essential if regenerative agriculture is to move from a compelling set of principles to a widely practiced, well-supported farming system.

Conclusion

Regenerative agriculture offers something genuinely different from earlier alternative farming movements: a shared, outcome-based language for measuring whether a farm is getting healthier over time, regardless of which specific inputs or certifications it carries. Its five core principles- minimal disturbance, continuous cover, living roots, diversity, and livestock integration are not new inventions so much as a rediscovery and systematization of practices that many traditional farming systems once followed as a matter of course. The path to wider adoption runs through patient institutional support

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credit, extension, and markets willing to work on a multi-year timeline rather than through any single technological fix. Done well, regenerative agriculture offers a rare proposition in modern farming: a way to keep producing food today while genuinely leaving the land in better condition for the generation that farms it next.

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The Rise of Agri-Startups: Transforming India's Rural Economy

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Abstract

India's agriculture sector is undergoing a technology-led transformation driven by a new generation of agri-startups. This article traces how policy support, including Startup India, RKVY-RAFTAAR, and the Agriculture Infrastructure Fund, has combined with rising digital penetration to fuel a diverse startup ecosystem spanning farm advisory, full-stack value chains, supply-chain logistics, agri-input e-commerce, precision drones, agri-fintech, and dairy technology. It examines the sector's impact on rural livelihoods, employment, and post-harvest losses, the recent cooling and maturing of venture funding, and the critical role of extension networks such as KVKs and ATMA in driving genuine, trust-based adoption. Drawing brief comparisons with Kenya, Brazil, and China, the article concludes that the sector's long-term success will depend on deeper partnership between private innovation and public agricultural research and extension systems.

Introduction

India's countryside is in the middle of a quiet but far-reaching transformation. For decades, the image of Indian agriculture was defined by fragmented landholdings, unpredictable monsoons, weak market linkages, and a widening gap between what a farmer earns and what a consumer pays. Today, a new generation of entrepreneurs is challenging that image. Agri-startups young companies built around technology, data, and innovative business models are stepping into the spaces that government schemes and traditional markets have struggled to fill.

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From drones that spray pesticide over a hundred acres in a day to mobile apps that connect a farmer in Vidarbha directly with a retailer in Mumbai, agri-startups are not just digitizing old processes; they are creating entirely new ways of producing, moving, financing, and selling food. This article looks at how this movement began, where it stands today, the areas it is reshaping, and the road ahead.

Why this Moment Matters

India's agriculture sector supports the livelihoods of nearly half the workforce yet contributes a much smaller share to national income, a mismatch that has long signaled low productivity and poor value capture at the farm level. Over 140 million smallholder households cultivate land in India, most operating on less than two hectares, and until recently, less than one percent of this vast base had any meaningful exposure to digital tools.

That is changing fast. Rising smartphone penetration, cheaper mobile data, government digital infrastructure such as e-NAM and the Agriculture Infrastructure Fund, and a wave of venture capital interest in food and farming have combined to create fertile ground for agri-startups. Analysts tracking the sector count several thousand agriculture-focused startups operating in India today, with new companies continuing to be registered each year even as investors have grown more selective about where they place their money.

The Policy Push Behind the Boom

Agri-startups did not emerge in isolation; they have grown alongside a deliberate policy push. The Startup India initiative, launched in 2016, gave young agri-ventures tax benefits, easier compliance, and access to seed funding. Schemes such as RKVY-RAFTAAR (Rashtriya Krishi Vikas Yojana) specifically earmark funds for agri-entrepreneurship, agribusiness incubators, and venture capital assistance for agri-startups.

The Agriculture Infrastructure Fund has channeled long-term, low-interest financing into post-harvest infrastructure, cold storage, warehousing, and primary processing units, much of which has been taken up by startups rather than large corporations. Meanwhile, ICAR institutions and agricultural universities have set up Agri-Business Incubators (ABIs) under the NAHEP and RKVY frameworks, mentoring young founders and connecting them with research that would otherwise stay confined to laboratories.

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State governments have joined in too. Karnataka, Maharashtra, and Telangana have built dedicated agritech innovation hubs, while Uttar Pradesh has pushed to link its network of Krishi Vigyan Kendras with incubation cells so that farmer-facing innovations move faster from pilot to scale.

Mapping the Agri-Startup Landscape

Agri-startups in India today can be grouped into a few broad categories, each solving a different piece of the value chain.

1. Farm Advisory and Precision Agriculture

Startups in this category use satellite imagery, weather modeling, and AI to give farmers hyperlocal advice on sowing windows, pest outbreaks, irrigation scheduling, and fertilizer dosage. Platforms built on this model have expanded their reach to farmers across several states, often bundling advisory services with input supply and credit facilitation so that a single app becomes a farmer's one-stop resource.

2. Full-Stack Agri-Value Chain Platforms

A number of well-funded startups have built end-to-end platforms that combine input supply, farm advisory, credit access, and output procurement under one roof. One such platform, operating across a dozen states, crossed over three thousand crore rupees in revenue in FY25 with an eleven percent year-on-year rise, turned a net profit of over three hundred and sixty crore rupees, and now exports processed agri-produce to more than thirty countries. This model reduces the number of intermediaries a farmer must deal with and gives startups the data needed to offer tailored credit and insurance products.

3. Farm-to-Retail Supply Chain Startups

These ventures focus on the gap between farm gate and retail shelf. By aggregating produce directly from farmer groups and moving it through organized cold chains to kirana stores, hotels, and modern retail, they cut out multiple layers of traditional mandi intermediaries, improving price realization for farmers while reducing wastage that has historically eaten into post-harvest value.

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4. Agri-Input and E-commerce Platforms

Online marketplaces for seeds, fertilizers, crop protection products, and farm equipment have grown rapidly, especially in Tier-2 and Tier-3 towns. One such marketplace crossed eleven hundred crore rupees in revenue in FY25 while expanding profitability, serving farmers across several southern and western states through its app, website, and multilingual phone support a reminder that voice and vernacular access remain essential in rural India.

5. Precision Agriculture Hardware and Drones

Drone-based startups have moved from pilot projects to commercial-scale operations, spraying nutrients and crop protection chemicals over large farm areas in a fraction of the time manual labor would require. Leading domestic drone manufacturers now account for a majority share of India's precision agritech drone market, operating fleets of trained pilots across dozens of cities and building toward public listings as the sector matures a sign of how far agri-hardware has come from being a niche, import-dependent segment.

6. Agri-Fintech and Commodity Trading

Startups working at the intersection of agriculture and finance are digitizing grain commerce, offering warehouse receipt financing, and building integrated platforms for post-harvest credit. Some of these platforms have become the only profitable agritech ventures at real scale in the country, recently raising some of the largest funding rounds the sector has seen, a sign that investors are rewarding capital-efficient, revenue-generating models over pure growth-at-any-cost strategies.

7. Livestock and Dairy Technology

Beyond crop farming, startups are bringing IoT-based herd management, milk quality testing, and cold-chain solutions to India's dairy sector, still the backbone of income for millions of smallholder and landless rural households, helping cooperatives and private dairies alike improve yield tracking and reduce spoilage losses.

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Table 1: Agri-Startup Categories at a Glance

Category	What It Solves	Typical Rural Impact
Farm Advisory & Precision Ag	Weather risk, input misuse, yield gaps	Better sowing/spray timing, lower input cost
Full-Stack Value Chain Platforms	Fragmented input, credit, and output access	Fewer intermediaries, more predictable income
Farm-to-Retail Supply Chains	Post-harvest loss, weak price realization	Higher farm-gate prices, less spoilage
Agri-Input E-commerce	Poor access to quality inputs in small towns	Wider input choice, competitive pricing
Drones & Precision Hardware	Labour shortage, slow spraying, over-application	Faster operations, new local jobs (pilots)
Agri-Fintech & Commodity Trading	Limited formal credit, weak warehouse finance	Faster loans, better use of stored produce
Livestock & Dairy Technology	Herd health tracking, milk quality loss	Higher yield realization, reduced spoilage

Impact on the Rural Economy

The cumulative effect of these ventures is visible in several dimensions of rural life. Farmers who once depended entirely on local commission agents now have access to price discovery tools and direct market linkages, narrowing (though not eliminating) the information asymmetry that has historically worked against them. Access to formal credit, once the near-exclusive preserve of nationalized banks and cooperative societies, is expanding through startup-led alternative credit scoring models that use farm data rather than only land records or credit history.

Employment generation is another important thread. Beyond the young founders and technologists based in cities, agri-startups create substantial rural employment as drone pilots, field agronomists, warehouse operators, last-mile delivery agents, and franchise partners running village-level service centers. For many rural youths, these roles are the first formal-sector jobs available in their own villages, reducing distress migration to cities.

Post-harvest losses, long estimated to run into thousands of crores of rupees annually in India, are gradually declining wherever startups have built organized cold-chain and storage infrastructure. And export-oriented full-stack platforms are giving Indian smallholder produce access to international markets that individual farmers could never have reached on their own.

Voices from the Ground: How Adoption Actually Happens

Policy documents and funding numbers tell only part of the story; the real test of any agri-startup is whether a farmer in a district like Bareilly, Nalanda, or Nashik chooses to use it season after season. Field surveys by agricultural universities suggest that adoption tends to follow a familiar pattern: a lead farmer or progressive cultivator in a village tries a new advisory app or drone service first, often at a demonstration organized jointly by a Krishi Vigyan Kendra and a startup's local franchise partner. If the results are visible within one or two seasons a saved spray round, a better price at sale, a reduction in urea overuse neighboring farmers follow.

This word-of-mouth, trust-based diffusion mirrors the classic pattern extension scientists have long studied, and it is precisely where startups often need public institutions the most. A slick app interface cannot replace the credibility that a KVK subject-matter specialist or a respected local ATMA functionary carries in a farming community. The startups that have scaled fastest and most sustainably tend to be the ones that have built genuine local partnerships rather than trying to bypass existing extension networks altogether.

Women and Youth in the Agri-Startup Story

An often-overlooked dimension of this transformation is who is doing the work at the ground level. Many agri-startups now train and deploy local women as village-level service point operators, handling everything from input bookings to soil-testing sample collection, giving rural women a formal, income-generating role that was previously unavailable to them. Similarly, youth who might otherwise have migrated to cities in search of employment are increasingly finding roles as drone pilots, data collection agents, and micro-franchise operators within a few kilometers of home.

This is a meaningful shift for India's rural demography. Distress migration driven purely by the absence of local opportunity has long been a feature of agrarian life in states such as Uttar Pradesh, Bihar, and parts of Madhya Pradesh. While agri-startups alone cannot reverse this trend, the formal, skill-based rural jobs they are creating offer a genuine, if still modest, counterweight.

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Learning from Global Comparisons

India is not alone in this transformation, and looking outward offers useful perspective. In Kenya, mobile-money-linked agri-platforms such as those built on the M-Pesa ecosystem have shown how digital finance and farm advisory can be bundled together for smallholders with limited banking access, a model Indian fintech-linked agri-startups are beginning to mirror. In Brazil, close collaboration between private agri-input companies and the public research body EMBRAPA has produced technology that is both commercially viable and scientifically validated for local soil and climate conditions, a partnership model Indian ABIs are trying to replicate through ICAR linkages.

China's rapid build-out of rural e-commerce logistics, anchored by platforms like Pinduoduo and Alibaba's rural initiatives, offers a caution and a lesson in equal measure: aggressive, capital-heavy expansion can transform farm-to-consumer logistics quickly, but without careful attention to farmer bargaining power, the gains can concentrate around the platform rather than the producer. Indian agri-startups and policymakers alike would do well to study these examples closely as the sector here matures.

Funding Trends: Enthusiasm Tempered by Caution

Venture investment in Indian agritech rose sharply through the pandemic years, peaking at over a billion dollars in annual funding around 2021 as investors bet on accelerated rural digitization. Since then, the funding climate has cooled and matured. Industry trackers estimate that agritech companies in India raised well over a billion dollars in 2024, but early data for 2026 shows a noticeable pullback compared to the previous year, with investors funneling money into fewer, more capital-efficient companies rather than spreading bets widely.

This shift mirrors a broader pattern across Indian startups: the era of growth-at-all-costs is giving way to scrutiny of unit economics, profitability, and genuine farmer impact. Maharashtra, Gujarat, and Karnataka currently host the largest concentrations of registered agri-startups in the country, while emerging states such as Assam are beginning to build their own smaller but steadily growing startup bases, often anchored by state agricultural universities and KVK networks.

Challenges That Remain

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Despite genuine progress, the agri-startup movement faces real constraints. Smallholder farmers remain price-sensitive and risk-averse, making adoption of paid digital services slower than app download numbers might suggest. Connectivity gaps persist in the remotest villages, and digital literacy, particularly among older farmers, continues to limit how deeply these platforms can penetrate.

Reaching the last mile is also expensive. Startups that build their own logistics and service networks in dispersed rural geographies often find their cost-to-serve rising faster than their revenue per farmer, a tension that has forced several companies to shut down or consolidate over the past few years. Competition among well-funded platforms for the same farmer base has intensified, particularly in the advisory and input-supply space, squeezing margins across the board.

There are also structural questions about data ownership and farmer consent, as startups collect increasingly granular information on land, cropping patterns, and financial behavior. And with several agri-startups now approaching public listings, questions of long-term governance and accountability to farmer-users, not just to investors, will only grow more pressing.

The Road Ahead

The next phase of India's agri-startup story is likely to be defined less by the number of new apps launched and more by depth of impact and integration. Convergence of technologies satellite data, IoT sensors, artificial intelligence, and drones working together rather than in silos is expected to make advisory services sharper and more predictive. Closer collaboration between startups and public research institutions, including ICAR bodies and state agricultural universities, could help startups build products grounded in locally validated science rather than generic models.

Extension functionaries, ATMA units, and Krishi Vigyan Kendras have a meaningful role to play here too, not as competitors to private agri-startups, but as trusted local partners who can help validate new technologies for farmers and build the last-mile trust that no app alone can manufacture. If public extension systems and private agri-innovation can work in genuine partnership, India's rural economy stands to gain far more than either could deliver alone.

Conclusion

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Agri-startups have moved from the margins of India's startup story to its centre, addressing problems that have troubled Indian agriculture for generations: poor price realization, weak credit access, high post-harvest losses, and limited access to modern farming knowledge. The sector is not without its difficulties, and not every venture will survive the current, more disciplined funding environment. But the direction of change is unmistakable. A rural economy once defined by information gaps and intermediation is slowly being rebuilt around data, direct market access, and locally relevant innovation, and that shift, more than any single startup's success, is the real story of transformation underway in India's villages.

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Strengthening Dairy Farmers Through Climate-Resilient Farmer Producer Organizations

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Collective action can help dairy farmers manage climate risks, reduce costs and build more resilient livelihoods

Abstract:

While dairy farming contributes to the incomes and livelihood security of millions of rural households, it is also facing new challenges due to climate change, such as increases in temperature, heat stress, lack of fodder, water scarcity, and disease incidence and animal reproductive performance. In the case of heat stress, it does directly impact the profitability of the farm by decreasing feed intake, milk production and reproductive efficiency (Gujar et al., 2025). The adoption of suitable technologies and inputs, knowledge, veterinary services and markets, at the right time is a major need of the climate resilient dairy farming system. Farmer Producer Organizations (FPOs) can be a good institutionalized approach to collectively provide these resources. Bulk procurement, shared veterinary services, vegetable climate advisories, milk aggregation, value addition and good market linkages offer new economic opportunities and an opportunity for the individual farmers to reduce their vulnerability through FPOs. There has been recent evidence from India showing that Farmers' Groups (FPOs) can boost farmers' climate adaptability by changing their behaviour and making them resilient to climate change (Rajak & Sathu, 2026). The article emphasizes on the importance of collective action, scientific knowledge and enterprise development using suitable technology in the context of market-oriented dairy development to create a robust dairy livelihoods support system for climate resilient dairy based FPOs.

Keywords: Dairy farming, Farmer Producer Organizations, climate resilience, heat stress, fodder security, collective action, dairy entrepreneurship

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Introduction:

A dairy farmer doesn't care about climate change in isolation; it's a reality for them. This concerns the farmer and his dairy herd and concerns climate change. This can be felt first-hand in the shed where it can manifest as a hotter shed, less feed consumption, decreased milk output, fodder shortages, reproductive problems and increased animal-health risks.

A few of these difficulties are particularly important, such as heat stress. As the temperature and humidity increases, dairy animals will have less ability to lose heat. They will decrease feed intake, change their behaviour, and if heat stress lasts for more than a few days, production, reproduction and physiological health will be impacted. Recently, a systematic review of the research on dairy cattle was conducted and the importance of heat stress management for animal welfare and productivity in the face of changing climate conditions was emphasized (Gujar et al., 2025).

Recent research in India also highlights the growing interest in the climate adaptation of dairy farming practices by the farmers, which is crucial in ensuring the continuity of milk production and adaptive capacity and livelihood security (Thakur et al., 2025). The challenge is not just to look after production of milk but also to keep healthy and productive animals in ever changing climate conditions.

Why Individual Farmers Cannot Face the Challenge Alone

The implementation of many interventions that are climate resilient involve resources, some of which may not be readily available to one smallholder. The farmer might require better fodder, quality feed, mineral supplements, veterinary services, cooling facilities, and/or better market facilities. Buying or making each one of these separately, may lead to higher costs and less feasibility for adoption.

Collective action is where it's helpful.

The FPO can provide the platform for farmers to come together to collectively demand for the services, negotiate and coordinate the services then develop businesses around their common needs. The FPO can order bigger quantity of feed and fodder seed instead of individual farmers ordering a small quantity of feed/fodder seed. The organisation can arrange veterinary camps and/or service agreements instead of individual farmers arranging services.

It is simple, the **basic principle** is:

When farmers join forces what can be difficult and costly to one is easier and less expensive to the others.

Building Climate-Resilient Dairy Enterprises

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Creating dairy enterprises that are resilient to climate change. An FPO with a dairy theme has the potential to be helpful to all aspects of the dairy value chain.

1. The first one is input security and fodder security. Group procurement of inputs such as feed, mineral mixtures, fodder seed and others can increase input availability and can help to cut transaction costs. It is also possible that FPOs can establish collective fodder enterprises, and promote hay/silage production to have fodder reserves during low availability seasons.
2. The latter is animal health and climate advisory services. An FPO can provide linkage to the veterinary services, animal health workers, breeding services and climate advice. The availability of weather and temperature-humidity data via mobile phones can be used to inform farmers to take precautionary actions prior to when high heat levels are reached.
3. The third is a common use of technology. Some cooling systems, water management systems, sensors, weather monitoring devices and other technologies might be too costly for the single farmer. The FPO can offer them the facilities, such as shared services or they can buy the facilities collectively.

This means that a solution to dairy farming that is resilient to climate change cannot be just a single intervention. This is a combination of housing, water, food, feed, health and management of breeding, monitoring and decision making at the appropriate time. In another study conducted in India in the past few years, the focus was on how climate change impacts the dairy industry and the need to make it more resilient, highlighting the importance of cooling, feed management, and heat-tolerant animals and sustainable technologies (Verma et al., 2025).

FPOs as Climate-Information Hubs

FPOs are regarded as Climate-Information Hubs. The best asset in times of climatic stress is the right information at the right time. The farmer should be aware of the time of extreme heat, if fodder supplies might become scarce, when extra cooling facilities are needed, and what steps need to be taken in terms of health care should be taken to prevent problems. An FPO can be a local forum for accepting, understanding and sharing this information.

Climate advisories can be translated into simple messages, for instance:

Predict heat wave → use water resources more readily available to keep animals cool/wet and ventilated, shift feeding to cooler times of day, watch for animals that are at risk. This translates to climate information to farm action.

Significantly, the empirical evidence is recent which directly underpins this institutional role. A study of 326 smallholder farmers in 38 FPOs in three agroecological regions of India by Rajak and Sathu

(2026) showed that institutional support to the farmers through the FPOs helped them in achieving climate adaptability in behavioural and psychological aspects.

These indicate that FPOs can play a role in climate resilient farming not just as a source of input but as enablers to learn, adapt and respond collectively among farmers. It takes just a single step from milk producer to dairy entrepreneur. Profitability has to be a part of the climate resilience equation, too. If dairy income is unpredictable, a farmer is not able to make continual investments in adaptation.

The economic aspect of resilience can be boosted via milk aggregation, quality testing, organised milk marketing and milk value-added by FPOs. Economically viable products other than raw milk such as paneer, curd, ghee and other processed milk products can be considered by the farmer groups. An opportunity for value addition is given to help retain more value in the producer community.

Then the change can then be from: Individual milk producer to Collective milk producer to Aggregator to Processor to Dairy entrepreneur This is especially critical since a dairy system that is resilient is one that not only must safeguard the animal, but the income of the household relying on that animal.

The transformation can therefore move from:

Individual milk producer → Collective milk producer → Aggregator → Processor → Dairy entrepreneur

This is particularly important because a resilient dairy system must protect not only the animal but also the **income of the household dependent on that animal**.

Women at the Centre of Dairy Resilience

The Center of Dairy Resilience will focus on women's issues and the steps they can take to improve their resilience. Women are also involved in dairy activities such as feeding, milking and running the animals and do household level livestock management activities on a large scale. But they might not be using formal markets and decision-making processes to a full extent.

Women can be given opportunities to be a member, shareholder, director and entrepreneur in the dairy focused FPOs. But opportunities for women to be more involved in income generation can be developed through collective enterprises involving milk aggregation, fodder production, and dairy processing and value added products.

Therefore, enhancing the dairy FPOs will help in achieving two kinds of resilience:

Animals and rural households which are resilient.

What a Climate-Resilient Dairy FPO Should Provide

A strong dairy FPO does not need to provide every service itself. It should build a network that connects farmers with the right institutions and services.

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Its priorities can include:

Area	Role of the FPO
Fodder security	Collective fodder production, seed procurement and silage
Feed & minerals	Bulk procurement of quality inputs
Animal health	Veterinary camps and health-service linkages
Heat management	Climate advisories and cooling solutions
Breeding	Access to timely reproductive services
Technology	Shared access to monitoring and advisory tools
Milk marketing	Aggregation, quality testing and organized sales
Value addition	Processing, packaging and branding
Training	Farmer capacity building and demonstrations
Finance	Linkages with banks and other financial institutions

The objective is not to create another layer of administration. It is to create a **functional support system around the dairy farmer**.

The Challenge: An FPO Must Be More Than a Name

It is not the aim to add another level of administration. That is to develop a viable support system for the dairy farmer. There is no resilience per se in dairy FPOs.

The organization should be well funded, managed by a professional team, have adequate working capital and have clear governance and functioning members. Patil et al. (2025) conducted a systematic review of FPOs in India in 2025, which revealed that financial constraints, managerial capacity, and market access and organization sustainability remain the ongoing challenges for FPOs.

Technical capacity is the other need for dairy FPOs which are aiming to be climate resilient. Up-to-date and accurate information is required by the directors and managers on livestock nutrition, animal health, climate risk, fodder planning and suitable technologies. It is therefore recommended that the FPOs establish good relationships with various veterinary institutions, KVKs, ICAR institutes, animal husbandry departments, dairy institutions, financial institutions and markets.

Way Forward

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The science and community action approach is what will make dairy resilient.

Withstand the effects of climate change through technology is only effective if farmers can use and implement it. Likewise, the collective organizations are successful if they deliver services that are needed to address farmers' problems.

So a feasible way is:

Climate information → Collective planning → Sharing resources → Scientific practices → Increasing productivity → Improved markets → Increased resilience of livelihoods

FPOs could be the institutional link between these. Their function needs to evolve beyond just collecting milk or inputs to being climate-smart dairy enterprises that assist the farmers in managing production risks, lowering production costs, access technology and generating maximum value from the production.

Conclusion

The climate is affecting dairy farmers' working conditions. The milk production capacity and household income may be at risk because of increasing temperatures, water scarcity, lack of fodder and risks of animal diseases. However, farmer-to-farmer climate resiliency building isn't necessary.

By bringing together dairy farmers, they are able to gain access to resources, knowledge, technologies and markets that will help them cope with a changing climate. A dairy FPO can offer fodder security, animal-health services, climate information, shared technologies, improved markets and value-addion opportunities, all of which can make it a climate-resilient dairy FPO. Most important, it can shift the focus from individual responsibility to collective action to handle climate change adaptations.

Climate change shouldn't be the only challenge the dairy farmer has to take. Strong organizations are essential to strong farmers—and strong organizations can help to use climate change as an opportunity to become stronger dairy enterprises.

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Climate-Resilient Dairy Farming: Practical Solutions for Farmers

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Keeping animals healthy, productive and profitable in a changing climate

Abstract

Dairy production is vulnerable to climate change impacts, such as rising temperatures, heat waves, irregular rainfall patterns, water shortages, and changing disease dynamics, and is becoming more vulnerable over time. One of these problems is heat stress which may lower feed intake, milk production, reproductive performance, and animal health. Heat-stress management has come under the spotlight in recent times as a crucial aspect of sustainable dairy production in the context of climate change (Gujar et al., 2025; Dhillon & Singh, 2025). Thus, an integrated approach to housing, feeding, watering, animal health, breeding and farm management is needed for climate resilient dairy farming. Good management practices like providing enough shade and ventilation, providing easy access to clean water, feeding during cooler periods, planning for better feed, mineral supplements, more heat-tolerant animals and early detection of any health issues can significantly increase the dairy animal's ability to withstand climatic stress. Advancements like the temperature-humidity monitoring tool, as well as digital advisories, can assist in making timely decisions. This introduces some simple and inexpensive solutions which dairy farmers can implement to ensure animal health, productivity and to build the resilience and profitability of dairy farming.

Keywords: Climate-resilient dairy farming, heat stress, dairy animals, fodder management, animal health, climate change, sustainable dairy production

Climate Change: A New Challenge for Dairy Farmers

The delicate balance between the animal, the feed, water, housing, and environment around the animal is required for dairy farming. Climate change is interfering with this balance. Direct effects on animal comfort and productivity include the impact of increased temperatures, extended heat waves, and changes in rainfall patterns and/or availability of forage. Heat stress is of great concern because dairy animals generate a lot of heat as they consume feed and convert it into milk.

Animals decrease feed consumption and water intake when it gets too hot and humid.

Animals may stand for longer or pant more often than usual and change their normal behaviour. Heat stress may cause the production of milk as well as reproductive, immunological, and health issues (Gujar et al., 2025). Heat stress has also emerged as a challenge in Indian dairy production in a recent review of Indian dairy farming with impacts on milk production, feed intake, reproductive efficiency and disease occurrence reported (Gautam et al., 2025).

So it is not just about more milk production in climate-resilient dairy farming. It is the care to maintain the animal's health and productivity even under adverse climatic conditions.

1. **Make the Shed a Heat-Resistant Shelter**

Install insulating material around exterior of the Shed and also insulate the outside of the Shed. The dairy shed is the first line of defence to heat stress. Sheds with poor ventilation will provide an even more stressful environment for the animals. Farmers need to ensure that adequate shade, air movement and space between animals is provided. The roof should minimise direct heat gain and the shed should be sited and designed to promote natural ventilation, if possible. Any trees in the vicinity of the dairy unit can also offer great shade.

Sprinklers, foggers or controlled water-spraying and good ventilation will aid animals in heat to dissipate heat. But, it doesn't always help animals to cool down if the animals are wet, but there isn't enough ventilation. In the recent guidance given by *Indian Farming*, one of the crucial components of heat stress mitigation in dairy animals are housing and cooling management systems (Dhillon & Singh, 2025). The three elements of shade, air movement and cooling all go together and are simple to apply to ensure better animal comfort.

2. Water Is the First Climate-Resilience Tool

During hot weather, to build up capacity in the field, the first Climate-Resilience tool is water. In hot weather water can become one of the most critical inputs to a dairy farm. The water intake of heat stressed animals will be elevated to keep their body temperature down and to meet physiological needs. Farmers need, therefore, to make a point of providing farm animals with clean and good quality drinking water on a 24/7 basis. Water troughs need to be clean and placed in convenient locations, avoiding the animals becoming overcrowded at the water trough. It's important to check water availability especially during the heat of the day. Excessive dry periods can lead to more heat stress, and have adverse effects on feed intake and production. One of the easiest and quickest measures that can be taken is to make sure that water is available to the dairy farmer when a heat wave strikes.

3. Change the Feeding Time During Hot Weather

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The animal's feeding behaviour is affected by heat. These increases in temperatures tend to cause animals to eat less and as a result, the nutrients in the feed and thus milk production may be lower. A good approach is to feed a higher percentage of the daily ration at cooler times of the day like early morning & early evening.

Only fresh, palatable and good quality feed should be given and avoid unnecessary wastage of feed. When heat stress decreases feed intake, good quality green feed and well-balanced rations can help to keep nutrient intake up. When making significant changes to the concentrate or mineral supplement a farmer should also consult their vet or animal nutritionist.

It's straightforward: If the animal refuses feed due to the heat, then every kg of feed will count.

4. Build a Fodder Security System

Fodder security is an integral part of climate resilient dairy farming. The availability of green fodder and the cost of feed might decrease as a result of drought and/or excessive rainfall and heat wave conditions. This vulnerability can be mitigated by planning with farmers on fodder production throughout the year and building up of fodder reserves. There are times when there is a shortage of forage and these can be filled in with other specific fodder varieties, suitable crop residues, hay or silage.

The use of silage is especially beneficial as it provides a means of storing excess green feed when this is not available. The planning of fodder should, therefore, be considered an investment in climate-resilience and not only as a feeding task. Alternatively, farmers have the option of diversifying fodder sources in addition to relying on one source, if they can.

5. Minerals and Nutritional Support Matter

Heat stress can disrupt normal physiological and/or metabolic processes. Changes in feed and water consumption coupled with an increase in the amount of sweat lost may affect electrolyte status and nutrient needs. The appropriate mineral mixture and a ration that is properly formulated can aid in animal health and productivity.

Specific supplements like buffers, antioxidants or any other nutritional intervention could be beneficial in specific cases; however, the addition of such supplements and their dosage should depend on the animal's physiological state and on nutritional information from a professional. The key is that: Avoid only cooling the animal as a response to climate stress, provide animal with nutritional support.

6. Protect Reproductive Performance

Heat stress is a problem with respect to milk production only. There may also be a fall in the reproductive performance. Reproducing efficiency, conception and expression of oestrus can be

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affected by high environmental temperatures. Under extended heat stress conditions, animals may exhibit subnormal and/or minimal signs of oestrus, making the detection of oestrus more challenging. Reproductive monitoring should, therefore, be given special attention during hot times for farmers. Preventive heat detection, breeding management, nutritional and veterinary management are important factors that can minimize reproductive losses. It is important to maintain reproductive efficiency as a loss of conception can have an impact on whole farm economics.

7. Give Special Attention to Calves and Vulnerable Animals

All animals are not alike when it comes to climatic stress. Preventing additional stress on calves, high-yielding animals, animals in the reproductive stage and animals with chronic health issues may require extra care. Young calves require proper weather, clean and dry housing, good nutrition and protection from the weather extremes.

A careful management of the animals should be added to the pregnant and high producing ones as their physiological demands are higher. Farmers should be on the lookout for any changes in the animals, such as:

The amount of feed and water consumed.

- Respiration and panting
- Milk production
- Behaviour
- Body condition
- Signs of disease
- Reproductive activity

8. Use the Temperature-Humidity Index as an Early Warning

Heat stress cannot be completely defined by temperature. Humidity also has a negative impact on heat loss from the animal by evaporation. That is the reason the Temperature-Humidity Index (THI), is commonly used to determine heat-load conditions for dairy animals. Farmers can implement heat stress prevention strategies earlier rather than waiting to see when animals start exhibiting severe heat stress symptoms to the weather, as they can use weather information and THI-based heat stress advisories. New microclimatic technologies are making the monitoring more readily possible.

ICAR has recently brought a microclimate monitoring technology to the forefront that enables the generation of microclimate fine scale data and facilitates livestock comfort assessment and timely interventions to mitigate heat stress and humidity stress. This is a significant change: From reacting to heat stress → to predicting and preventing heat stress.

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9. Select Animals for Resilience

A climate resilient animal is the first step towards long-term climate resilience. Adaptation to the local environment should be taken into account, in addition to productivity, in breeding and selection programs. An animal that yields a lot of milk, but does not do well in the local climatic conditions, will need a lot more management input. Thus, farmers and breeding programmes should take into account other components of the farm or breeding program's performance, such as those associated with health, fertility, adaptability and longevity.

This is not to say that animals should be selected just because they are considered to be "heat tolerant. When deciding on a breed, the suitability of the environment, production system, feed resources, disease conditions and veterinary support should be taken into consideration. A productive animal is worth something; a productive animal, that will stay healthy in the locality is even more valuable.

10. Use Technology for Timely Decisions

Make timely decisions with the use of Technology. The use of technology is slowly making its way into the world of livestock farming and production that is becoming climate resistant. Farmers can be provided with prediction of environmental stress well in advance with the help of weather stations, temperature-humidity sensors, automated monitoring system and digital advisory platforms.

Precision-livestock technologies are also being developed to more accurately detect animal behaviour and physiological parameters in real time to detect heat stress earlier. The recent study on thermal stress assessment has shown the emerging technologies to assess and monitor the thermal stress in dairy cattle (Singaravadivelan et al., 2025). Technologies, however, need not be about the expensive investment of equipment for smallholders. Farmer groups, cooperatives and FPOs have the potential to deliver shared services of weather stations, sensors, advisory services and veterinary technologies.

11. Manage the Farm as a Complete System

There is no single practice that can be relied upon to create a climate resilient habitat. The animal could still be heat stressed if the only shade provided is from a farmer and the water supplies are inadequate. Likewise, under- or over-exposure to high temperatures won't be made up for by good feed, or by cooling facilities will not overcome long-term feed shortages.

A dairy farm that is resilient will employ a number of measures: If the housing, water, feeding, fodder security, animal health, reproductive management, monitoring and timely interventions are all good, then the animal is good. If all the above are good, all the animal is good. It's the collective power that's there, not the individual interventions.

A Practical Climate-Resilient Dairy Checklist

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For farmers looking for a simple starting point, the following measures can make a meaningful difference:

Area	**Practical action**
Housing	Provide shade, ventilation and sufficient space
Water	Ensure continuous access to clean drinking water
Cooling	Use sprinklers/fans where feasible during severe heat
Feeding	Offer more feed during cooler hours
Fodder	Maintain green fodder, hay and silage reserves
Nutrition	Provide a balanced ration and appropriate mineral supplementation
Health	Monitor animals daily and respond early to illness
Reproduction	Give extra attention to heat detection and breeding
Monitoring	Use weather/THI information for early warning
Technology	Adopt affordable digital or sensor-based monitoring where useful
Collective action	Use FPOs/cooperatives for shared inputs and services

From Surviving Climate Stress to Building Resilience

Climate-resilient dairy farming doesn't imply getting rid of all the impacts of climate change. It involves enhancing animals' and farmers' resilience to climatic stress and faster recovery and operations.

This involves changing the approach from "solution" to "prevention". When milk production declines, it is too late, but when a heat wave arrives, it's time to get ready. They should make fodder reserve rather than delay due to shortage of fodder. They should improve the preventive health management rather than waiting for the manifestation of the diseases.

This is an important skill to be able to foresee risks, which will be increasingly crucial in the future for the dairy industry.

Conclusion:

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Climate change is not only an environment problem; it is also a farm-management problem. Increased heat and changes in climate can impact animal comfort, milk yield, reproduction and profitability for dairy producers.

Luckily, many of the solutions that are climate resilient do not involve any high-tech solutions. The cornerstones of a resilient dairy farm can be shade, ventilation, clean water, planned feeding, fodder reserves, balanced nutrition and preventive health care and timely monitoring.

The use of technology can anchor these efforts within the context of weather monitoring and weather-based advisories, as well as Weather Wiser and other new precision-livestock technologies. Collective organizations can also help lower the input, services and technologies costs.

The aim is not just to save the lives of the animals during harsh weather. The aim is to ensure to maintain animal health, comfort and productivity whilst ensuring the livelihood of the farmer is safeguarded.

Climate resilient dairy farming is not a technology, but an ongoing process that requires multiple interventions and adaptations over time. It's a long-term management strategy that is building resilience for the future climate of the farm.

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Recent Advances in Fish Health Management in Indian Aquaculture: Challenges and Future Perspectives

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Abstract

Indian aquaculture, contributing over 8% of global fish production, faces escalating threats from infectious diseases that cause significant economic losses annually. This review examines the current landscape of fish health challenges in Indian aquaculture systems, with a focus on bacterial, viral, parasitic, and fungal pathogens affecting key cultured species such as rohu (Labeo rohita), catla (Catla catla), pangasius (Pangasianodon hypophthalmus), and Pacific white shrimp (Litopenaeus vannamei). Recent advances in biosecurity frameworks, molecular diagnostics including loop-mediated isothermal amplification (LAMP) and multiplex PCR, the application of probiotics and immunostimulants derived from indigenous bacterial strains, and early-stage vaccination research are discussed. Despite promising developments, challenges persist in farmer adoption, cold-chain infrastructure, antimicrobial resistance, and regulatory frameworks governing veterinary drug use in aquaculture. This article argues for an integrated fish health management approach combining surveillance, science-based biosecurity, and sustainable therapeutics to secure the future productivity and profitability of Indian aquaculture.

Keywords: Fish health management; Indian aquaculture; bacterial diseases; probiotics; biosecurity; molecular diagnostics

1. Introduction

India is the second-largest fish-producing nation in the world, with an annual output exceeding 17.5 million metric tonnes as reported by the Department of Fisheries, Government of India (2023). Inland aquaculture contributes nearly 65% of this total, making it a critical sector for food security, rural livelihoods, and foreign exchange earnings. The sector supports the livelihoods of over 28 million people engaged directly or indirectly in fishing and fish farming (FAO, 2022).

However, the rapid intensification of aquaculture production, driven by growing domestic and export demand, has come at a cost. High stocking densities, sub-optimal water quality management,

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overreliance on prophylactic antibiotic use, and inadequate biosecurity measures have created conditions favorable for the emergence and spread of pathogens. Disease outbreaks remain the single most significant constraint to sustainable aquaculture growth in India, with annual losses estimated at over ₹3,000 crores (Sahoo et al., 2022).

Fish health management—defined as a proactive, multidisciplinary approach encompassing disease prevention, surveillance, rapid diagnosis, treatment, and biosecurity—has received increased scientific and policy attention in recent years. This review synthesizes recent developments in this domain and discusses the barriers and opportunities that will define the future trajectory of fish health management in India.

2. Major Fish Health Challenges in Indian Aquaculture

The spectrum of diseases affecting Indian aquaculture is broad, spanning bacterial, viral, parasitic, and fungal etiologies. Among bacterial pathogens, Aeromonas hydrophila remains the most ubiquitous threat, responsible for epizootic ulcerative syndrome (EUS) and hemorrhagic septicemia in carps. Edwardsiellosis caused by Edwardsiella tarda has been documented in catfish and major carps across Andhra Pradesh, West Bengal, and Odisha (Kumar et al., 2020). Columnaris disease (Flavobacterium columnare) has emerged as a significant problem in intensive freshwater pond systems.

Viral diseases have gained prominence with the expansion of shrimp culture. White spot syndrome virus (WSSV) continues to devastate penaeid shrimp farms along the coastline, with reported mortality rates of up to 100% within days of outbreak. Infectious hypodermal and hematopoietic necrosis virus (IHHNV), Taura syndrome virus, and more recently, Decapod iridescent virus 1 (DIV1) have been recorded from shrimp farms in Gujarat, Andhra Pradesh, and Tamil Nadu (Rameshkumar et al., 2021).

In the freshwater sector, koi herpesvirus (KHV) poses a significant threat to common carp (Cyprinus carpio) culture. Parasitic infestations by Argulus spp., Dactylogyrus spp., and Gyrodactylus spp. cause chronic stress and act as entry points for secondary bacterial infections. Branchiomycosis (gill rot) caused by Branchiomyces sanguinis and B. demigrans has been increasingly reported in stagnant, eutrophic ponds (Mohan et al., 2019).

Antimicrobial resistance (AMR) presents a growing cross-cutting challenge. A study conducted by Panda et al. (2021) across fish farms in Odisha found multidrug-resistant Aeromonas isolates resistant to ampicillin, tetracycline, and trimethoprim-sulfamethoxazole, commonly used antibiotics in

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aquaculture. The irrational use of antibiotics—often without veterinary prescription—is widespread and represents both a public health and ecological risk.

3. Recent Advances in Fish Health Management

3.1 Biosecurity

Biosecurity in aquaculture encompasses all measures taken to prevent the introduction and spread of pathogens within and between farms. The National Fisheries Development Board (NFDB) and ICAR-Central Institute of Freshwater Aquaculture (CIFA) have promoted the adoption of farm-level biosecurity protocols, including source verification of seed, quarantine of new stock, and disinfection of water inputs (NFDB, 2021).

A landmark development has been the introduction of the MPEDA (Marine Products Export Development Authority) biosecurity certification scheme for shrimp farms targeting export markets. Farms following certified biosecurity protocols reported 35–40% reduction in disease-related losses compared to non-certified farms in a three-year observational study in Andhra Pradesh (Anand et al., 2022). All-in, all-out stocking, pond preparation with lime, and exclusion netting to prevent bird predation and pathogen spread have been identified as the most cost-effective individual measures.

3.2 Rapid Diagnostics

Early and accurate disease diagnosis is fundamental to effective management. Traditional culture-based methods, while reliable, are time-consuming and unsuitable for farm-level deployment. The past decade has witnessed significant advances in molecular diagnostic tools applicable to Indian conditions.

Loop-mediated isothermal amplification (LAMP) assays developed for WSSV, EMS/AHPND-causing Vibrio parahaemolyticus, and Aeromonas hydrophila have demonstrated sensitivity and specificity comparable to real-time PCR, with results achievable in under 60 minutes without specialized equipment (Mohanty et al., 2021). ICAR-CIBA (Central Institute of Brackishwater Aquaculture) has validated LAMP-based field kits for WSSV and DIV1 detection, and pilot deployment has been undertaken in Tamil Nadu and Andhra Pradesh.

Point-of-care lateral flow immunoassay strips for WSSV antigen detection have been developed in collaboration with private diagnostics firms and are now commercially available at a cost of under ₹200 per test (Singh et al., 2022). Multiplex PCR panels targeting five shrimp pathogens simultaneously have been standardized by ICAR-CIBA, reducing diagnostic turnaround from days to hours. Next-generation sequencing (NGS)-based metagenomic surveillance is being piloted through a collaborative project between IIT Madras and ICAR to characterize the full pathobiome of cultured fish and shrimp.

3.3 Probiotics and Immunostimulants

The use of probiotics as alternatives to antibiotic growth promoters has gained substantial scientific support in Indian aquaculture. Indigenous strains of Bacillus subtilis, Lactobacillus plantarum, and Saccharomyces cerevisiae have been evaluated across multiple ICAR institutes and state agricultural universities.

A controlled trial by Dash et al. (2020) at ICAR-CIFA demonstrated that dietary supplementation of rohu fingerlings with Bacillus subtilis (10^7 CFU/g feed) for 60 days resulted in a 28% improvement in specific growth rate, significant upregulation of lysozyme activity, and a 45% reduction in mortality following experimental Aeromonas hydrophila challenge. Similar findings have been reported for Labeo rohita fed Lactobacillus-fermented diets in West Bengal by Roy et al. (2021).

Immunostimulants derived from natural sources—including beta-glucans extracted from yeast cell walls, levamisole, and herbal extracts of Ocimum sanctum, Azadirachta indica, and Withania somnifera—have shown promise in enhancing non-specific immune responses in carps and shrimp. A study by Krishnan et al. (2022) in Tamil Nadu shrimp farms found that dietary supplementation with β-1,3/1,6-glucan at 0.1% feed inclusion improved survival against WSSV challenge by 32% under controlled conditions. Commercial probiotic formulations combining Bacillus, Lactobacillus, and Nitrosomonas strains are now widely available in the Indian market, though quality standardization remains inconsistent.

3.4 Vaccination

Vaccination represents the most sustainable long-term strategy for disease control but remains underdeveloped in Indian aquaculture relative to its potential. ICAR-CIFA has made notable progress in developing injectable oil-adjuvanted bacterins against Aeromonas hydrophila and Edwardsiella tarda for carps. Field trials of the Aeromonas bacterin in Andhra Pradesh and Odisha demonstrated 60–75% relative percent survival (RPS) in vaccinated rohu compared to unvaccinated controls (Sahoo et al., 2020).

Immersion vaccines—more practical for large-scale fingerling immunization—are being evaluated for column disease and Flavobacterium infections. DNA vaccines targeting conserved outer membrane

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proteins of Aeromonas hydrophila have advanced to proof-of-concept stages in laboratory settings (Nayak, 2021), though regulatory pathways for commercial approval remain undefined. The development of an oral vaccine delivery system using microencapsulated antigens represents a particularly promising frontier that could overcome the practical limitations of injection vaccination for small-scale farmers.

4. Challenges

Despite scientific progress, several systemic barriers impede effective fish health management at the farm level in India. First, the fragmented nature of Indian aquaculture—dominated by small-scale farmers with average pond sizes below 1 hectare—limits the adoption of capital-intensive technologies. Diagnostic services remain geographically concentrated in state capitals and research institutes, with little penetration into rural fish farming clusters.

Regulatory gaps are a significant concern. There is no dedicated veterinary drug regulatory framework for aquaculture species under the Drugs and Cosmetics Act; antimicrobials registered for terrestrial livestock are used empirically in fish farming without dose standardization. The absence of maximum residue limits (MRLs) for many antibiotics in aquaculture products in Indian legislation creates export rejection risks and public health concerns (Pattanaik et al., 2020).

Cold-chain infrastructure deficiencies affect the deployment of live probiotic products and biologicals, particularly in remote aquaculture zones. Farmer awareness of fish health management remains limited, and extension services—once the backbone of aquaculture knowledge transfer—have weakened considerably over the past two decades. Climate change compounds these challenges by altering thermal regimes and rainfall patterns that drive pathogen dynamics and bloom events in aquaculture water bodies (Padiyar et al., 2021).

5. Future Perspectives

The future of fish health management in India must be built on three intersecting pillars: integrated surveillance, farmer-accessible technology, and an enabling regulatory environment. A national aquatic animal disease surveillance network—modeled on the OIE (now WOAH) framework—connecting district veterinary hospitals, state fisheries laboratories, and ICAR institutes through a digital reporting platform would enable real-time outbreak tracking and early warning.

Artificial intelligence and machine learning applications in aquaculture are being explored globally for disease early warning based on behavioral biomarkers detected through computer vision systems.

Indian institutions including IIT Delhi and ICAR-CIFE have begun exploratory work in this space. Similarly, the integration of environmental DNA (eDNA) monitoring for early pathogen detection in pond water represents a non-invasive surveillance tool with significant potential for large-scale deployment.

The microbiome of farmed fish and their rearing environment is an emerging research frontier. Characterizing the core microbiome of healthy Indian carps and shrimp, and understanding how management practices, diet, and disease shift microbiome composition, will inform next-generation probiotic strategies. Phage therapy—using bacteriophages to target antibiotic-resistant Aeromonas and Vibrio strains—merits accelerated research investment as a precision alternative to broad-spectrum antibiotics (Das et al., 2022).

From a policy standpoint, a dedicated aquatic animal health policy, establishment of fish health clinics at block levels, and mandatory prescriber certification for aquaculture antimicrobial use are urgently needed reforms. International collaborations under frameworks such as the Bay of Bengal Large Marine Ecosystem (BOBLME) project can support transboundary disease surveillance, particularly for viral pathogens capable of rapid spread along migratory corridors.

6. Conclusion

Fish health management in Indian aquaculture stands at a critical inflection point. The scientific foundations—advanced diagnostics, efficacious probiotics, promising vaccine candidates, and evidence-based biosecurity frameworks—are increasingly available. The challenge now is one of translation: moving these tools from research stations to the ponds of millions of small-scale farmers across the country. A coordinated national response integrating research, extension, regulation, and farmer empowerment is essential if India is to sustain and expand its aquaculture productivity while safeguarding public health and ecological integrity. With appropriate investment and policy will, fish health management can transition from a reactive crisis response to a proactive system of prevention, surveillance, and sustainable productivity.