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Gender Roles in Agriculture and the Effectiveness of Extension Services: A Pathway to Inclusive Rural Development

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Abstract

Agriculture is a pillar industry that supports livelihoods and food security especially in the developing countries where a large percentage of the population rely on it. In this industry, gender is an important factor in determining access to resources, contribution to labour, decision-making and embracing new technologies. The agricultural workforce is dominated largely by women, who are also subject to enduring inequalities in access to land, credit, inputs and extension services. This review is a critical analysis of the role that gender plays in agriculture and the effectiveness of agricultural extension systems in alleviating gender disparities. It also addresses the social-economic and institutional obstacles, evaluates the effects of gender-inclusive extension strategies and suggests gender mainstreaming strategies. The research points out that to improve productivity, sustainability and rural development, it is important to empower woman and make the extension systems gender responsive.

Keywords: Gender, Women Farmers, Agricultural Extension, Empowerment, Rural Development, Gender Equality

1. Introduction

Agriculture is also an important sector to the economic growth, employment creation and food security, particularly in such countries as India where a significant percentage of the population is in rural communities. Gender, which is defined as the socially constructed roles and responsibilities of men and women, plays a significant role in participation in agricultural activities and access to resources (World Bank, 2012). Women have an irreplaceable role in agriculture, as they contribute to the various farm and allied activities; but their contributions are often underestimated because of the socio-cultural norms and institutional biases. The Food and Agriculture Organization state that women constitute about 43% of the world agricultural labour force (FAO, 2011). Nevertheless, women farmers are systemically disadvantaged and cannot be as productive and economically promising as men (Doss, 2018). The agricultural extension services, designed to provide knowledge and enhance agriculture practices, have long been male dominated and have failed to address the specific needs of the women farmers (Meinzen-Dick *et al*., 2014). Thus, it is essential to learn the role of genders and integrate gender views into the extension services in the quest to realize equitable and sustainable agricultural development.

2. Role of Women in Agriculture

The women are actively engaged in nearly all agricultural activities such as land preparation, sowing, transplanting, weeding, irrigation, harvesting, threshing and after-harvest processing. Along with crop production, women are an important source of livestock management, fisheries and agro-processing activities, hence contributing to household income and food security (Agarwal, 2010). In most of the developing nations, women are left to do subsistence farming and provide nutrition to the household. Nevertheless, their input frequently does not make it to official statistics and economic evaluations. The role of women goes beyond the production to the selection of seeds, their preservation and indigenous knowledge systems, which are essential in conservation of biodiversity and sustainable farming. In spite of their significant contribution, women tend to work on smaller plots, limited access to better technologies and limited access to better extension services (Quisumbing *et al*., 2014). According to an estimation by FAO (2011), should women be granted the same access to productive resources as men, agricultural yields could improve by up to 20–30 percent, which would greatly reduce world hunger and poverty.

Table 1 - Gender Roles in Agricultural Activities

Activity	**Men's Role**	**Women's Role**
Land Preparation	Ploughing, machinery operation	Limited involvement

Sowing/Transplanting	Supervision, seed selection	Active participation
Weeding	Occasional participation	Major responsibility
Irrigation	Operation of irrigation systems	Assisting role
Harvesting	Cutting, transport	Cutting, collection, bundling
Post-harvest Processing	Marketing, storage decisions	Cleaning, drying, grading

3. Gender Disparities in Agriculture

The problem of gender inequalities in agriculture is a complex and multi-layered issue that encompasses socio-cultural, economic and institutional aspects. Among the greatest inequalities is the inequalities in access to resources including land, credit, inputs and technology. The ownership of land is also a major determinant of economic empowerment and decision-making power but this is rarely the case as women rarely own land due to laws governing inheritance and traditional practices (Agarwal, 2010). This deprivation deprives them of the opportunity of accessing institutional credit and government schemes and hence their productivity is hampered. Moreover, women tend to have low involvement in the process of making decisions both at home and in the community even when they make a significant contribution to agricultural labour (Doss, 2018). Another big problem is wage inequality, as women agricultural labourers often earn less than men working in the same sector (ILO, 2016). Such differences are not only impacting on the livelihood of women but also has a wider implication of agricultural productivity and rural development.

Table 2. Gender Disparities in Access to Agricultural Resources

Resource	Men	Women	Implication
Land Ownership	High	Very Low	Limited decision-making power
Credit Access	Easier access	Restricted access	Lower investment capacity
Extension Services	High outreach	Limited outreach	Reduced adoption of technologies
Inputs (Seeds, Fertilizers)	Better access	Limited access	Lower productivity

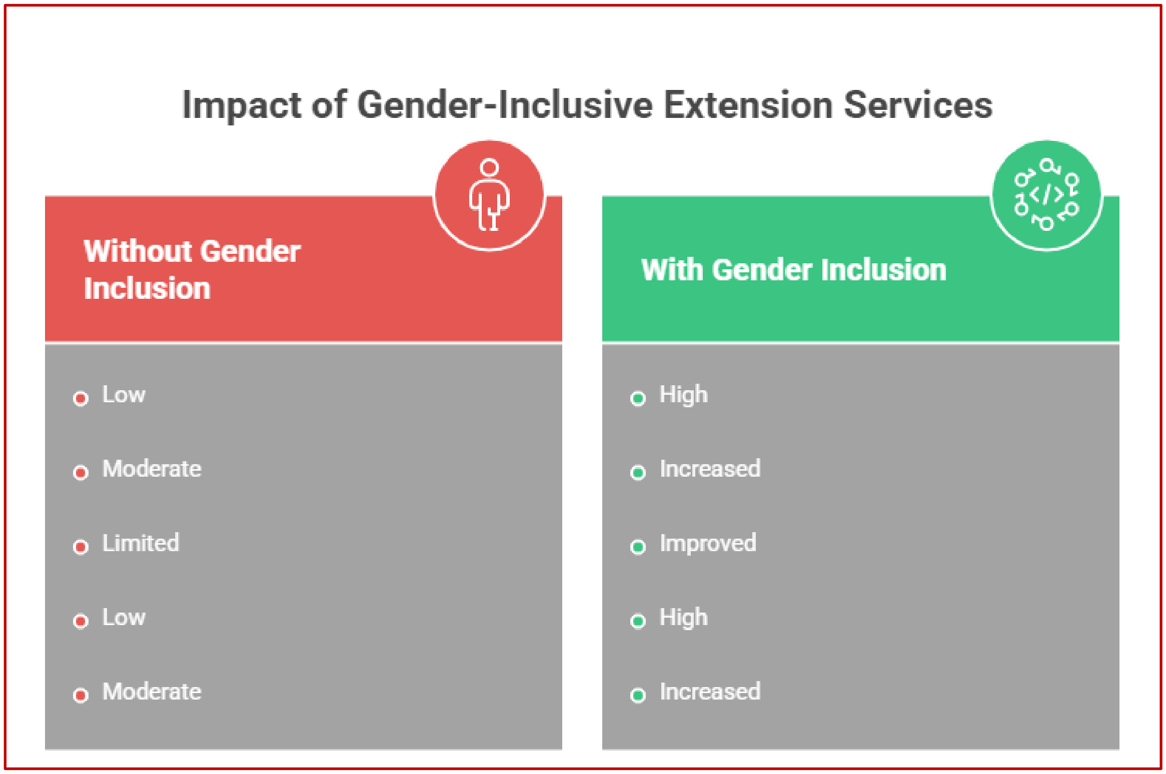
Training Programs	Frequent participation	Less participation	Knowledge gap

4. Gender and Agricultural Extension Services

Agricultural extension services are critical for transferring knowledge, technologies and innovations to farmers. However, traditional extension systems have largely been designed with a male-centric perspective, often neglecting the needs and constraints of women farmers. Extension agents are predominantly male and interactions are typically directed towards male household heads, which limits women's access to information and training (Meinzen-Dick *et al.*, 2014). Additionally, women face time constraints due to their dual responsibilities in household and farm work, which restrict their participation in extension programs and training sessions (Ragasa *et al.*, 2013). Mobility constraints and socio-cultural norms further hinder their engagement with extension services. Moreover, extension programs often fail to consider gender-specific needs, such as access to labour-saving technologies, nutrition-sensitive agriculture and income-generating activities suitable for women (World Bank, 2012). As a result, women remain excluded from the benefits of agricultural innovations, leading to lower productivity and income.

5. Impact of Gender-Inclusive Extension Services

Gender-inclusive extension services have the potential to significantly improve agricultural productivity, food security and rural livelihoods. When women are provided with equal access to information, training and resources, they are more likely to adopt improved agricultural practices and technologies (Ragasa *et al.*, 2013). Studies have shown that empowering women through extension services leads to better household nutrition, as women tend to allocate resources towards food, health and education (Quisumbing *et al.*, 2014). Furthermore, gender-responsive extension approaches enhance women's decision-making power and participation in community development activities (Meinzen-Dick *et al.*, 2014). Participatory approaches, such as farmer field schools and self-help groups, have proven effective in engaging women and addressing their specific needs (Chambers, 1994). These approaches not only improve agricultural outcomes but also contribute to social empowerment and gender equality.



Impact of Gender-Inclusive Extension Services

Without Gender Inclusion	With Gender Inclusion
Low	High
Moderate	Increased
Limited	Improved
Low	High
Moderate	Increased

Fig. 1.1 – Impact of Gender – Inclusive Extension Services

6. Strategies for Gender Mainstreaming in Agriculture and Extension

Addressing gender disparities in agriculture requires a multi-dimensional approach that integrates gender considerations into policies, programs and institutional frameworks. Gender-sensitive policies are essential to ensure equal access to land, credit, inputs and extension services (FAO, 2011). Capacity-building initiatives should be designed to accommodate women's schedules, literacy levels and specific needs, thereby enhancing their participation and effectiveness (Ragasa *et al*., 2013). Increasing the number of female extension workers can improve communication and trust, making extension services more accessible to women farmers (Meinzen-Dick *et al*., 2014). The use of information and communication technologies (ICTs), such as mobile-based advisory services, can help overcome mobility constraints and provide timely information to women farmers (Aker, 2011). Participatory approaches that involve women in decision-making processes are also crucial for ensuring the relevance and sustainability of extension programs (Chambers, 1994). Additionally, strengthening women's collectives, such as self-help groups and farmer producer organizations, can enhance their bargaining power and access to markets.

7. Challenges and Future Perspectives

Although gender equality is increasingly recognized as the importance of it in agriculture, there are still certain challenges that exist. The socio-cultural norms remain deep-rooted which limit women's access to resources and participation in decision making. Gender disaggregated data is lacking and this makes it difficult to design targeted interventions and to measure their impact. Further, institutional constraints like inadequate funding and inadequate trained personnel, also constrain the gender responsive extension program. Extension systems need to be forward-thinking and embrace innovative methods that incorporate gender considerations, harness digital tools and encourage inclusive engagement in the future. Government collaboration, research institutions, NGO and private sector cooperation is crucial in establishing a conducive space for gender equality in agriculture. All these are challenges that must be overcome to reach sustainable development goals and food security.

8. Conclusion

Gender is a key determinant of agricultural systems and livelihoods in rural areas. Women play an important role in agricultural production, but there remains a number of constraints which hinder their potential. Agricultural extension services need to be more inclusive and responsive to the needs of women farmers. Increasing the empower of the women is not only a social justice issue, but also a strategic step towards improving the productivity and sustainability of agriculture. The gender gap that exists in agriculture can be bridged to achieve significant improvements in food security, economic growth and rural development.

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Digital Tools for Farmers: Bridging the Gap Between Lab and Land Through Smart Agricultural Technologies

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1. Introduction

Agricultural extension systems have traditionally served as the backbone for transferring knowledge from research institutions to farmers. However, these systems are often constrained by limited manpower, delayed communication and lack of contextual customization. In India, where over 85% of farmers are smallholders, the inefficiency of traditional extension methods results in delayed adoption of improved technologies (FAO, 2017).

The lab-to-land gap refers to the disconnect between agricultural innovations developed in research institutions and their actual implementation at the farm level. This gap is not merely informational but also structural, involving issues of accessibility, timeliness and relevance.

With the rapid advancement of digital technologies, agriculture is undergoing a paradigm shift. Digital agriculture enables real-time advisory, precision input management and data-driven decision-making, offering a scalable solution to bridge this gap.

2. Concept of Digital Agriculture

Digital agriculture refers to the integration of advanced technologies into farming systems to enhance productivity, sustainability and efficiency.

Key Categories of Digital Tools

Category	**Description**
Mobile Applications	Provide advisories, weather updates, market prices
IoT-based Systems	Sensors for soil moisture, climate, crop health
AI & Machine Learning	Predictive analytics for pests, yield, weather
Remote Sensing & GIS	Satellite-based monitoring and mapping

(Source: Adapted from World Bank (2019))

These tools transform raw data into actionable insights, enabling farmers to make informed decisions without requiring deep technical expertise.

3. Major Digital Tools and Platforms for Farmers

3.1. Kisan Suvidha

- Provides weather forecasts, input dealer information and advisories
- Helps farmers plan irrigation and crop protection activities

3.2. e-NAM (National Agriculture Market)

- Online trading platform integrating mandis across India
- Enhances price transparency and market access

3.3. Plantix

- AI-based mobile app for disease detection using image recognition
- Offers instant diagnosis and treatment suggestions

3.4. ICAR Digital Advisory Services

- Region-specific recommendations based on agro-climatic conditions
- Delivered via SMS, apps and call centers

Practical Benefits

- Reduced dependency on middlemen
- Timely decision-making
- Improved crop health management

4. Role of Computer Science in Agriculture

This section reflects the interdisciplinary integration brought by computer science.

4.1. Data Analytics in Crop Prediction

Large datasets from weather stations, soil sensors and satellite imagery are analyzed to predict crop performance.

4.2. AI-based Pest and Disease Detection

Machine learning models trained on image datasets can identify diseases with high accuracy, reducing diagnostic delays (Kamilaris & Prenafeta-Boldú, 2018).

4.3. Yield Forecasting Models

Algorithms use historical data and environmental variables to estimate yield, aiding policy and market planning.

4.4. IoT Sensors

Devices measure:

- Soil moisture
- Temperature
- Humidity

These sensors automate irrigation and optimize resource use.

4.5. Blockchain Technology

Ensures transparency in supply chains by recording transactions securely, reducing fraud and enhancing traceability.

5. Bridging Lab to Land: Mechanism & Impact

Digital tools act as intermediaries that convert scientific research into farmer-friendly advisories.

Mechanism

1. Data Collection (sensors, satellites)
2. Data Processing (AI/ML models)
3. Advisory Generation
4. Delivery via mobile platforms

Impact

- Faster dissemination of innovations
- Reduced information asymmetry

- Context-specific recommendations

6. Resource Efficiency & Productivity Gains

Digital agriculture significantly improves resource-use efficiency.

- **Water Use:** IoT-based irrigation reduces wastage by up to 30%
- **Fertilizer Application:** Precision farming ensures optimal input use
- **Pesticide Use:** Targeted application reduces environmental impact

Studies indicate that digital advisory services can increase yields by 10–20% under optimal conditions (World Bank, 2019).

7. Challenges and Ground Realities

- **Digital Literacy:** Many farmers lack the skills to use advanced tools
- **Connectivity Issues:** Poor internet access in rural areas
- **Trust Deficit:** Farmers rely more on traditional knowledge sources
- **Data Privacy:** Concerns over misuse of farm data
- **Cost Barriers:** High initial investment for devices and services

8. Future Prospects

The future of digital agriculture lies in deeper integration of technologies.

Emerging Trends

- AI-driven personalized advisory systems
- Big Data integration for predictive farming
- Climate-smart agriculture tools
- Integration with extension services

Interdisciplinary collaboration between agriculture and computer science will be essential to develop scalable and sustainable solutions.

9. Comparison of Traditional vs Digital Extension

Parameter	**Traditional Extension**	**Digital Extension**
Reach	Limited	Wide and scalable
Speed	Slow	Real-time
Customization	Generalized	Personalized
Cost Efficiency	High per farmer	Low per farmer
Feedback Mechanism	Weak	Instant

Source: FAO (2017)

10. Conclusion

Digital agriculture offers a scientifically sound and practically viable pathway to bridge the longstanding gap between research and field application. However, the assumption that technology alone can solve systemic agricultural challenges is flawed. Without addressing issues of accessibility, affordability and trust, digital tools risk becoming underutilized innovations.

A balanced approach is required—one that integrates digital technologies with traditional extension systems, strengthens institutional frameworks and prioritizes farmer capacity building. The future of agriculture depends not just on innovation, but on effective translation of knowledge into practice.

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Impact of Climate Change on Vegetable Crops: A Scientific Review

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Abstract

Vegetable crops occupy a central position in India's food security and farm economy, yet they are among the most climate-sensitive agricultural commodities. Rising temperatures, erratic rainfall, elevated atmospheric CO_2 and more frequent extreme weather events are disrupting crop physiology, reducing yields, altering nutritional quality and intensifying pest and disease pressure. This review synthesizes current evidence on how climate change is affecting vegetable production, both globally and in the Indian context, covering physiological responses, crop-specific vulnerabilities (tomato, potato, cauliflower, leafy greens, cucurbits), nutritional implications and adaptation strategies. Key gaps in India-specific research are also identified. The overall aim is to provide a grounded, practical understanding that can inform research priorities and on-ground decision-making for smallholder vegetable farmers who face disproportionate climate risks.

Keywords: *Climate change, Vegetable crops, Heat stress, Drought, Food security, Adaptation*

1. Introduction

The global climate has already warmed by approximately 1.1°C above pre-industrial levels, with projections of a further 1.5–4.0°C rise by 2100 (IPCC, 2021). In India, 2023 was among the warmest years on record, with rising night-time temperatures, shifting monsoon patterns and more frequent extreme events documented across major vegetable-growing states (IMD, 2023). These trends are not merely meteorological abstractions, instead, they are reshaping when, where and how much vegetables can be grown.

Vegetable crops are inherently more climate-sensitive than cereal crops. Their fast growth cycles, narrow thermal optima and high water demands make them especially vulnerable to variability. India produces over 200 million tonnes of vegetables annually (NHB, 2022) and this sector underpins rural livelihoods and urban nutrition for hundreds of millions. Understanding how climate change is affecting vegetable production, and what can be done about it, is therefore a matter of considerable urgency.

2. Key Climate Stressors Affecting Vegetable Production

2.1 Temperature Rise

Temperature governs germination, photosynthesis, flowering and fruit development in vegetable crops. Photosynthesis in most vegetables peaks between 20–30°C; beyond 35°C, the enzyme *Rubisco* loses efficiency, photorespiration increases and chlorophyll can degrade (Wahid et al., 2007). Crucially, elevated night-time temperatures accelerate respiration, diverting photosynthates away from yield-forming organs and reducing harvest indices. In reproductive terms, temperatures above 32°C during anthesis cause pollen sterility in tomato and pepper, resulting in flower drop and fruit abortion (Peet et al., 1998). For cool-season crops like cauliflower and peas, warming winters prevent adequate vernalization, so edible structures fail to form properly.

2.2 Rainfall Variability and Water Stress

India's monsoon is becoming less predictable: the IMD has documented significant variability in onset timing, spatial distribution and intensity across key vegetable-producing states (IMD, 2023). Drought during the reproductive stage of tomato, brinjal or okra causes flower and fruit drop. Waterlogging from intense rainfall events promotes soil-borne pathogens and root asphyxiation. Pereira (2016) described this double-edged nature of water stress- inadequate and excessive moisture, as one of the most difficult management challenges under climate change.

2.3 Elevated CO_2 and Nutritional Quality

Atmospheric CO_2 has surpassed 420 ppm (NOAA, 2023). While elevated CO_2 can stimulate photosynthesis in C_3 vegetables, it simultaneously dilutes protein, iron, zinc and vitamins in plant tissues. Myers et al. (2014) demonstrated that crops grown under elevated CO_2 in Free Air CO_2 Enrichment (FACE) experiments contained meaningfully lower micronutrient concentrations. Dong et al. (2018) extended this to leafy vegetables, showing reduced B vitamins and nitrate. Heat stress further reduces vitamin C and other antioxidants. For India, where vegetables are often the primary affordable micronutrient source for lower-income households, this nutritional erosion is a serious, under-recognized dimension of climate change.

3. Crop-Specific Vulnerabilities

Table 1 summarizes the documented impacts of climate change on major vegetable crops grown in India.

Vegetable	Key Stressor	Main Effect	Estimated Impact	Reference
Tomato	Heat (>32°C)	Pollen sterility, lycopene loss	5–8% yield loss per °C	Peet et al., 1998
Potato	Heat (>25°C)	Tuber initiation failure	16–28% loss by 2050	Hijmans, 2003
Cauliflower	Warm winters	Poor curd development	40–60% area loss by 2080	Kumar et al., 2012
Leafy greens	Heat, elevated CO_2	Bolting, reduced nutrients	Seasonal loss significant	Dong et al., 2018
Cucurbits	High heat	Sex expression shift	Field-reported loss	Wahid et al., 2007

Table 1. Comparative impact of climate change on major vegetable crops (compiled from reviewed literature).

Tomato is the most studied and among the most vulnerable crops. Lycopene synthesis which is responsible for both colour and nutritional value, is suppressed above 32°C. For potato, Hijmans (2003) projected losses of 16–28% across South Asia by mid-century due to disrupted tuber initiation. In Himachal Pradesh, Kumar et al. (2012) estimated that climatically suitable area for cauliflower could shrink by 40–60% under high-emission scenarios by 2080, a projection with direct implications for mountain farming communities where vegetable cultivation is the primary livelihood. Singh et al. (2010) documented that the sowing window for rabi vegetables in the Indo-Gangetic plains has already narrowed by 10–15 days over the past three decades.

4. Pest and Disease Pressure

Climate change enhances the threat from both pests and pathogens. Warmer temperatures are expanding the range and increasing the reproductive rate of key pests: whiteflies (*Bemisia tabaci*), primary vectors of Tomato Yellow Leaf Curl Virus, thrive under elevated temperatures. Deutsch et al. (2018) projected that global crop losses to insect pests will increase substantially with every degree of warming, with tropical and sub-tropical regions like India facing disproportionately higher impacts.

Fungal and bacterial diseases also benefit from changing conditions. *Phytophthora infestans* (late blight) intensifies under warm and humid conditions increasingly common in the Nilgiris and Himalayan foothills. Bacterial wilt (*Ralstonia solanacearum*) is projected to expand its range northward in India as winter minimum temperatures rise, threatening solanaceous crops in states previously protected by cold winters.

5. Adaptation Strategies

Adaptation to climate change in vegetable production operates across several interconnected levels which are discussed in following sections.

Varietal improvement is the most durable long-term strategy. ICAR-IIVR (Varanasi) has released heat-tolerant lines of tomato and brinjal, and drought-tolerant okra lines are in advanced evaluation (ICAR-IIVR, 2021). Bita and Gerats (2013) identified pollen thermotolerance, membrane stability and antioxidant capacity as key molecular traits for selection under heat stress. Faster incorporation of these traits into farmer-accessible varieties is essential.

Agronomic adjustments offer near-term benefits: adjusted sowing dates to avoid peak heat during anthesis; use of 25–50% shade nets (which have demonstrated 15–20% yield improvement in summer tomato at IARI, New Delhi); mulching to moderate root-zone temperature and conserve moisture; and drip irrigation to optimize water delivery. Protected cultivation in polyhouses, shade-net houses and naturally ventilated greenhouses offers the most direct buffering against external climate variability and has already enabled year-round production in parts of Himachal Pradesh, Maharashtra and Gujarat, though high capital costs remain a barrier for smallholders.

At the policy level, weather-indexed crop insurance products designed specifically for vegetables, dedicated climate-adaptive vegetable research under ICAR, expansion of the National Horticulture Mission to explicitly incorporate climate risk and wider deployment of agro-meteorological advisory services through mobile platforms would make a tangible difference.

6. Conclusion

Climate change is already reshaping vegetable production in India and worldwide and the trajectory will intensify unless proactive adaptation is pursued at scale. The crops most central to India's food security and rural livelihoods such as tomato, cauliflower, potato, leafy greens face documented physiological stress, yield losses and nutritional degradation. The threat is compounded by expanding pest and disease pressure. Yet vegetable crops, by virtue of their short cycles and genetic diversity, are also amenable to rapid varietal improvement and agronomic adjustment. The science is clear on what needs to happen. The urgent need now is for policy investment and institutional will to implement solutions at the farm level, with particular attention to the smallholder farmers who bear the greatest risk and currently have the least support.

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Agrivoltaics: Harmonizing Renewable Energy Production with Sustainable Agriculture

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Abstract:

Agrivoltaics represents a transformative convergence of renewable energy production and sustainable agricultural practice, in which solar photovoltaic (PV) systems are harmoniously co-located with crop cultivation on the same land unit. As the global population is projected to reach 9.8 billion by 2050, escalating pressures on food, energy, and water resources necessitate transformative solutions. Agrivoltaics addresses this Food-Energy-Water (FEW) nexus by exploiting the principle of light sharing — strategically placing elevated solar panels above crops to capture excess solar radiation beyond plants' light saturation point, generating clean electricity while simultaneously creating a protective microclimate. This review consolidates current evidence on the agronomic, technological, economic, and environmental dimensions of agro-solar farming. Key findings indicate that agrivoltaic systems can reduce crop water requirements by 20–50%, lower sub-canopy temperatures by 2–8°C, and achieve Land Equivalent Ratios (LER) of 1.3–1.84, signifying substantially superior combined land productivity over separate systems. The global agrivoltaic market, surpassing 5 GW capacity by 2024, is projected to exceed USD 10 billion by 2030. With an estimated agrivoltaic potential of 3,156–13,803 GW, India is promoting adoption through schemes like PM-KUSUM and SKY, making agrivoltaics a key technology for climate-resilient agriculture despite economic and regulatory challenges.

Keywords: Agrivoltaics, Sustainable Agriculture, Land Equivalent Ratio, Photovoltaic, Light Saturation Point, Food-Energy-Water Nexus, PM-KUSUM.

1. Introduction

Agriculture and energy production have historically competed for land resources — two of humanity's most urgent needs locked in a zero-sum contest. Agrivoltaics — the deliberate co-location of solar photovoltaic (PV) systems and agricultural activities on the same parcel of land — offers a paradigm-shifting resolution to this conflict. The concept was first conceptualised by

Adolf Goetzberger and Armin Zastrow at Germany's Fraunhofer Institute in 1981, and practically demonstrated by Akira Nagashima in Japan in 2004 through his concept of "Solar Sharing," agrivoltaics has evolved from a theoretical curiosity to a globally scaling technology (Nagashima, 2004). Since then, it has rapidly evolved from niche pilot projects to a globally recognized Climate-Smart Agriculture (CSA) strategy.

The word 'harmonize' captures the essential promise of agrivoltaics — not a compromise between food and energy, but a genuine synergy where each system enhances the performance of the other. Solar panels moderate the crop microclimate while crops cool the panels; shading reduces water stress while the same land generates clean electricity. This review examines the scientific, technological, economic, and policy dimensions of this harmony.

The fundamental operating principle is Light Sharing. Most crops possess a biological "light saturation point" — a threshold beyond which additional photosynthetically active radiation (PAR, 400–700 nm) cannot be utilized for growth and instead causes heat stress and excessive transpiration. By strategically positioning solar panels above or between crop rows, excess light is captured for electricity generation while the panels simultaneously create a moderated, cooler microclimate — reducing water evaporation by up to 40–50% and shielding crops from extreme temperature events (Lokesh et al., 2024; Dupraz et al., 2011). This symbiotic relationship is further reinforced by the cooling effect of crop transpiration on panel surfaces, which can increase panel electricity generation efficiency by 1–3%.

According to the Food and Agriculture Organisation (FAO, 2018), Climate-Smart Agriculture (CSA) is an integrated approach that sustainably increases agricultural productivity, builds climate resilience, and reduces greenhouse gas emissions. Agrivoltaics satisfies all three pillars of CSA: it boosts productivity through dual-use land, enhances adaptation via microclimate modification, and contributes to mitigation by displacing fossil fuel-based electricity. The global agrivoltaic market is projected to exceed USD 10 billion by 2030, with installed capacity already surpassing 5 GW worldwide as of 2024 (GIZ, 2024).

2. System Components and Working Mechanism

Understanding how agrivoltaics achieves its dual-purpose harmony requires examining each component of the integrated system and the physical mechanisms through which energy and agricultural subsystems mutually reinforce one another. An agrivoltaic system is composed of five integrated subsystems, each critical to the dual-function output of electricity and food:

- **Solar PV Modules:** Bifacial modules (capturing light from both surfaces via the Albedo effect) and semi-transparent thin-film modules are preferred. Bifacial panels increase energy yield by 10–25% compared to conventional monofacial panels in raised setups.

- **Elevated Mounting Structures:** Steel or aluminium pillars raising panels 2.5–5.0 metres above ground, allowing tractor clearance and preventing heat entrapment beneath the array.
- **Inverters and Battery Storage:** Convert DC electricity to AC for on-site use (irrigation pumps, cold storage) or grid export under net-metering/feed-in-tariff mechanisms.
- **Monitoring and Sensing Systems:** Soil moisture sensors, pyranometers (light intensity meters), weather stations, and canopy temperature sensors enable precision management of both crop and energy subsystems.
- **Smart Irrigation and Self-Cleaning Modules:** Precision drip or fertigation systems integrated with automated panel-cleaning mechanisms that minimise water use while maintaining panel efficiency.

Working Mechanism — Light Sharing: The system exploits the biological light saturation point of crops (the threshold beyond which additional PAR causes heat stress rather than photosynthesis). Solar panels intercept this "excess" light for electricity generation, while allowing sufficient diffuse and transmitted PAR to reach the crop canopy below. Ground Coverage Ratios (GCR) in agrivoltaics are maintained at 30–50% (versus 60–70% in standard solar farms) to ensure adequate crop irradiation. A virtuous feedback loop is established: crops transpire water vapour, cooling the sub-panel microclimate; cooler panels operate more efficiently, generating up to 3% more electricity than panels over bare ground (Dinesh and Pearce, 2016). Panel temperatures can drop by 10–15°C compared to conventional ground-mount installation.

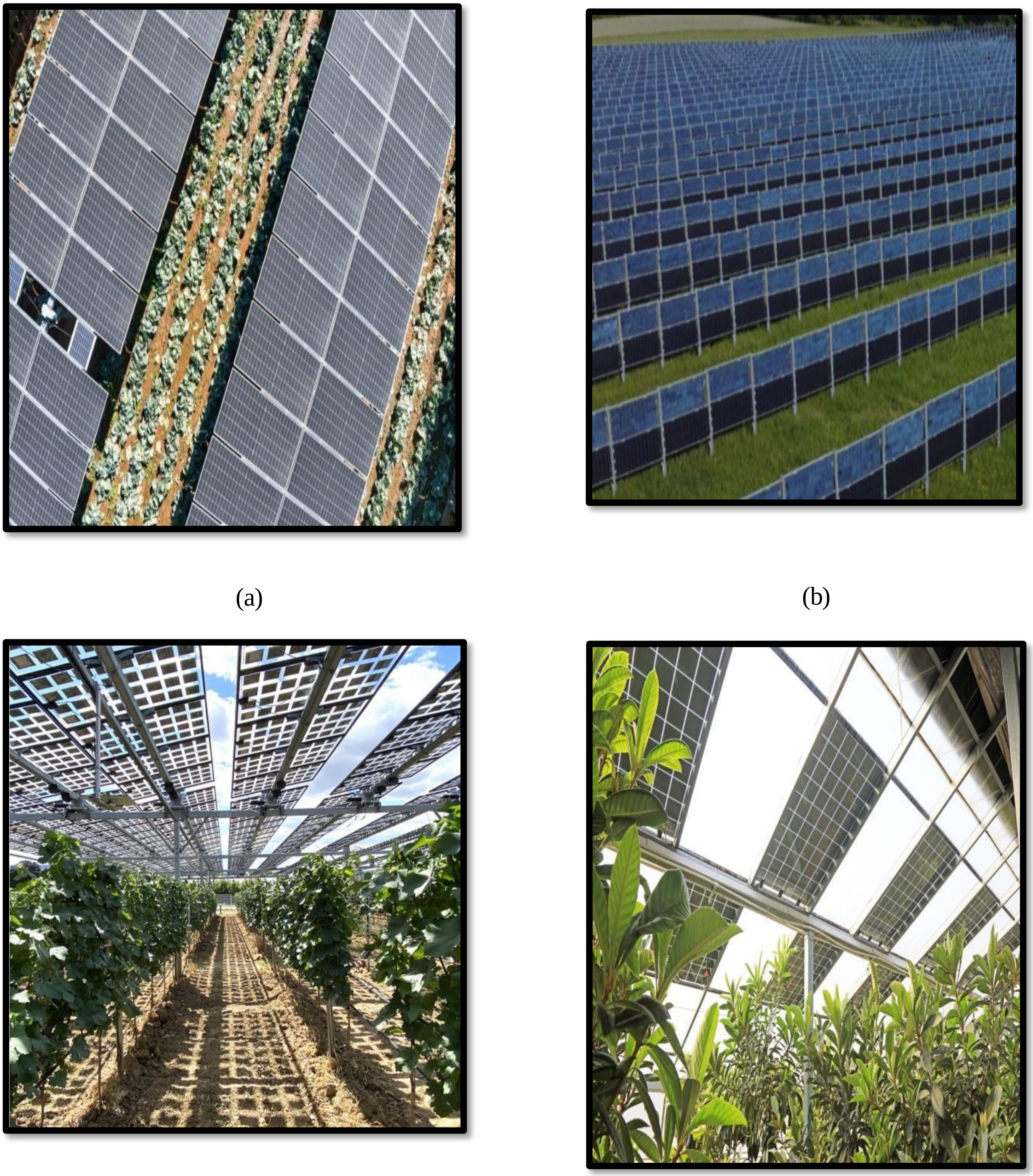
3. Types, Design and Technology

3.1 Major Agrivoltaic System Types

System Type	Configuration	Best Crop Fit	Key Advantage
Fixed Elevated /Overhead	Panels mounted on high stilts (2.5–5 m) with a spaced or checkerboard arrangement	Leafy greens, berries, fruit trees, livestock grazing	Maximizes land-use efficiency (LUE) and supports mechanized harvesting
Dynamic / Tracking	Panels tilt on single- or dual-axis systems with AI-controlled movement	Vineyards, high-value horticulture, orchards	Optimizes crop light availability and energy generation in real time

Vertical Bifacial	Upright fence-like bifacial panels arranged in north–south rows	Wheat, oats, maize, pasture grass	Allows full machinery access, reduces wind impact, and avoids overhead rain obstruction
Inter-row Farming	Conventional panels installed with widened spacing between rows for crop lanes	Sun-loving cereals such as wheat, maize, and rice	Uses standard ground-mounted panels, lowers installation cost, and remains mechanization-friendly
Greenhouse PV	Semi-transparent photovoltaic modules integrated into greenhouse roofs and walls	Tomatoes, cucumbers, flowers, controlled-environment horticulture	Enables year-round cultivation with self-powered climate control and urban adaptability

Table 1. Classification of agrivoltaic system types (Amaducci et al., 2018; Weselek et al., 2021)



(a) (b)

(c) (d)

Figure 1: Major Agrivoltaic system types (a) Fixed Elevated /Overhead system (b) Vertical Bifacial system (c) Inter-row Farming system (d) Greenhouse Photovoltaic system

3.2 Design Parameters

Optimal agrivoltaic design requires careful calibration of three primary physical parameters:

- Tilt Angle (20–25°): Panels are often set at shallower angles than latitude-optimal to allow more ground-level irradiation during critical crop growth stages. Dynamic single-axis trackers can rotate to vertical during heavy rain events, enabling full soil recharge.
- Row Spacing (Pitch): GCR of 30–50% is maintained. Row spacing (4–6 m between rows) is determined by farm machinery turning radius, ensuring safe tractor and harvester passage.
- Mounting Height (2.5–5 m): Provides tractor clearance, prevents thermal inversion under the array, and creates an adequate air buffer to moderate the sub-panel microclimate without over-shading.

3.3 Solar Cell Technologies for Agrivoltaics

Feature	**Monocrystalline**	**Polycrystalline**	**Thin-Film**	**Bifacial (Mono)**
Efficiency	19–22%	15–17%	10–13%	Up to 22%+
Durability	25–30 years	20–25 years	10–15 years	25–30 years
Heat Tolerance	Good	Fair	Best (stable)	Good
Best AV Use	Overhead elevated	Inter-row/Budget	Solar greenhouses	Vertical & high-yield
Visual	Uniform black	Speckled blue	Smooth/transparent	Glass-on-glass

Table 2. Comparison of solar cell types used in agrivoltaic applications (Mahmoud et al., 2025)

An important emerging technology is Spectral Splitting through Organic Photovoltaic (OPV) cells, which can be tuned to absorb wavelengths unused by crops (green light, UV, near-infrared) while transmitting the growth-critical red and blue PAR wavelengths. This represents the next frontier in light-use optimization within agrivoltaic systems (Modi et al., 2024).

4. Agricultural Aspects: Crops, Soil Health, and Microclimate

4.1 Crop Selection — Shade Tolerance Spectrum

Category	**Crop Examples**	**Notes**
Highly Suitable (Shade-Loving)	Lettuce, Spinach, Potatoes, Onions, Mushrooms, Ginger, Colocasia	Thrive under 20–50% shade; benefit most from microclimate cooling

Moderately Suitable	Tomatoes, Berries, Legumes (Green gram, Soybean — in interspaces), Cabbage	Yield comparable to open-field under well-designed inter-row systems
India-Specific HVCs	Aloe Vera, Medicinal plants, Saffron (Kashmir), Strawberries (MP), Herbs	High economic value; premium pricing offsets any yield reduction

Table 3. Crop suitability categories for agrivoltaic systems (Pawar et al., 2025)

4.2 Microclimate and Agronomic Benefits

The sub-panel microclimate is perhaps the clearest expression of the agrivoltaic harmony — a space where reduced radiation, buffered temperatures, and retained soil moisture collectively create growing conditions superior to open-field exposure for shade-tolerant species

- **Heat Stress Reduction**: Sub-panel air temperatures are 2–8°C lower than open-field conditions during peak summer, directly reducing crop heat stress and improving quality (Adeh et al., 2019).
- **Water Efficiency**: Shade reduces soil evaporation by 20–30%, cutting irrigation water requirements by 15–50% — critically important for India's water-stressed arid and semi-arid regions.
- **Soil Organic Carbon (SOC)**: Panel shading reduces soil temperatures by 5–10°C, slowing organic matter decomposition and promoting SOC accumulation.
- **Nutrient Retention**: Panels intercept heavy rainfall impact, reducing nutrient leaching and topsoil erosion. Field trials report higher N, P, and K levels in agrivoltaic plots compared to open-field controls (Giri and Mohanty, 2024).
- **Pest and Disease Management**: While increased humidity under panels can elevate fungal disease risk (root rot, powdery mildew), Integrated Pest Management (IPM) strategies — including resistant variety selection, strategic row spacing, precision monitoring, and biological control — effectively manage this risk.

5. Economics of Agrivoltaics Farming

The economic model of agrivoltaics is fundamentally a Dual-Revenue framework. While initial capital investment (CAPEX) is 15–30% higher than conventional ground-mount solar (due to elevated structures costing 50% more steel), the combined financial returns from electricity sales and crop production deliver substantially superior long-term economic performance.

Metric	Traditional Farming	Agrivoltaic System	Key Advantage
Annual Revenue	₹1.5–4 Lakh/ha (crop only)	₹25–40 Lakh (energy + crop)	~10× higher revenue
Payback Period	Seasonal (year-to-year)	4–7 years (with PM-KUSUM)	Guaranteed income
Annual ROI	2–8% (market-linked, variable)	12–16% (annual avg.)	Stable guaranteed income
Water Requirement	100% (high evaporation)	70–85% of baseline	15–30% water saving
Land Productivity	Baseline (1.0)	LER 1.3–1.84	60–84% more productive
Risk Profile	High (weather/market)	Low (guaranteed solar PPA)	Diversified income shield

Table 5. Economic comparison: Traditional farming vs. agrivoltaic dual-use systems (Wang and Chen, 2024)

The primary metric for evaluating agrivoltaic system productivity is the Land Equivalent Ratio (LER). The Land Equivalent Ratio (LER) is the mathematical expression of the agrivoltaic harmony: it quantifies the productive premium achieved when energy and food are co-produced on the same land compared to two separate systems.

LER = [Agricultural Yield (AV) ÷ Agricultural Yield (Monoculture)] + [Solar Yield (AV) ÷ Solar Yield (Conventional Solar)]

LER < 1.0 = Inefficient | LER = 1.0 = Neutral | LER > 1.0 = Productive (Dual-Use Advantage)

6. Indian Scenario

India's agrivoltaic potential is immense. A 2024 GIZ-Fraunhofer ISE report estimates a technical potential of 3,156–13,803 GW — far exceeding India's 500 GW renewable energy target. Critically, converting just 1% of India's cultivated land to agrivoltaics could generate over 600 GW of solar power while simultaneously preserving agricultural production.

6.1 Policy Framework

The Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme, particularly Component A, encourages farmers to install decentralised solar power plants (up to 2 MW) on barren or fallow land, which are readily adaptable to agrivoltaic models. Key state-level initiatives include:

- Gujarat — Suryashakti Kisan Yojana (SKY): 60% subsidy for panel installation with a government buy-back rate of ₹7/unit for the first 7 years.
- Maharashtra — Mukhyamantri Saur Krishi Vahini Yojana: Target of solarising 30% of

agricultural feeders by 2025 through cluster farming hubs.

- I-SUN Project: Partnership between the Government of Germany (GIZ) and India's Ministry of New and Renewable Energy (MNRE) exploring innovative solar applications (NISA) to minimise land use.

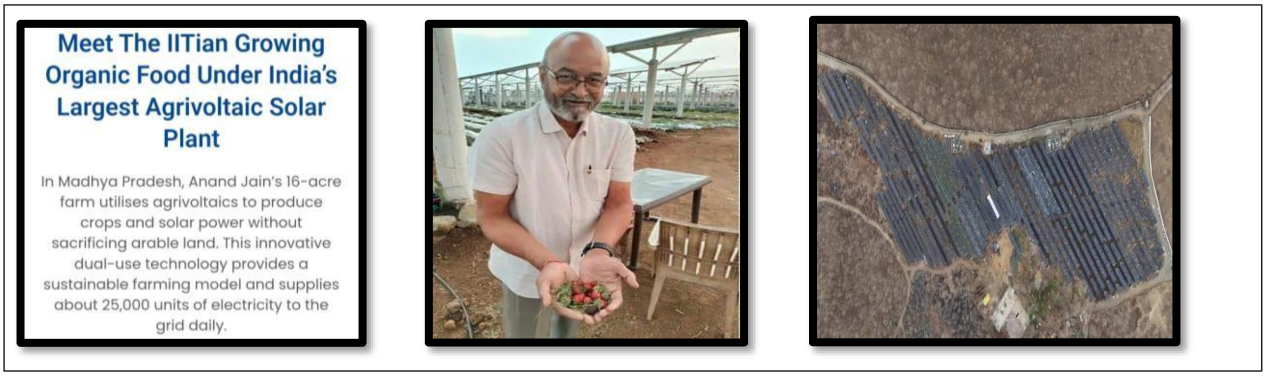
6.2 Key Stakeholders

Several premier Indian institutions are driving agrivoltaic research and deployment:

- National Institute of Solar Energy (NISE): R&D on crop-specific panel heights.
- ICAR: Identifying shade-tolerant indigenous crop varieties for diverse agro-climatic zones.
- Private Sector: Tata Power and Mahindra Susten exploring 'Vertical Solar Fencing' pilots in Punjab and Haryana.
- Anand Agricultural University (Gujarat): Collaborative research on agrivoltaic system performance for Kharif crops.

6.3 Notable Indian Success Stories

- **The "IITian's Organic Farm", Sagar, Madhya Pradesh:** India's largest private agrivoltaic plant (16 acres), developed by Anand Jain (IIT Roorkee alumnus). Panels mounted at 12–15 feet; crops include organic strawberries, broccoli, and lettuce. The farm generates 25,000 units of electricity daily — a prime example of Climate-Smart horticulture.



Meet The IITian Growing Organic Food Under India's Largest Agrivoltaic Solar Plant

In Madhya Pradesh, Anand Jain's 16-acre farm utilises agrivoltaics to produce crops and solar power without sacrificing arable land. This innovative dual-use technology provides a sustainable farming model and supplies about 25,000 units of electricity to the grid daily.

- **Amrol Distributed Solar Project, Anand, Gujarat:** 1 MW, 12-acre project by GIPCL and Anand Agricultural University. Tested groundnut, soybean, cotton, millet, wheat, and banana under partial shade. Proved Kharif crop viability under an agrivoltaic canopy and underpinned the SKY policy framework.

7. Barriers to Harmony: Challenges in Agrivoltaic Adoption

Despite significant promise, agrivoltaic adoption faces several interconnected barriers that must be addressed through technical innovation, policy reform, and financial instruments:

- **High Initial CAPEX:** Elevated agrivoltaic systems are 15–30% costlier than conventional solar setups, limiting affordability for small farmers.

- **Technical Complexity:** Systems require crop- and site-specific designs based on shading, machinery, and microclimate conditions.
- **Regulatory Gaps:** Lack of clear agrivoltaic land-use policies in India creates permitting and insurance challenges.
- **Equipment Damage Risk:** Farm machinery may accidentally damage mounting structures or solar panels during field operations.
- **Long-term Liability:** Long-term solar agreements often conflict with shorter agricultural planning cycles.
- **Rainwater Runoff:** Panel structures can concentrate rainfall at edges, causing uneven soil moisture and erosion.
- **Microclimate Pathogens:** Higher humidity and lower airflow under panels may increase fungal disease incidence.

8. The Future of Harmony: Emerging Technologies and Pathways

The future of agrivoltaics is being shaped by rapid advances in precision technology, materials science, and digital agriculture:

- **AI-Driven Agrivoltaics:** AI-based systems will optimize panel angles in real time using crop and sensor data to balance energy production and plant growth.
- **Organic Photovoltaics (OPV):** Flexible “smart shade” solar films will allow photosynthesis while generating electricity, reducing installation costs.
- **Autonomous Robotics:** Electric autonomous tractors will reduce labour needs and minimize machinery damage risks in agrivoltaic farms.
- **Harmonized Land-Use Policies:** Governments and the FAO are developing unified policies that officially recognize agrivoltaic land as a dual-use category for both agriculture and energy production.
- **Aquavoltaics:** Floating solar panels over fish ponds can reduce water evaporation and algal growth while producing clean energy.
- **Policy & Standardization:** Emerging design standards and supportive policies will simplify regulations and encourage wider adoption.
- **Integrated Food-Energy-Water Hubs:** Future systems will combine solar irrigation, cold storage, and EV charging to create self-sustaining farm energy hubs.

9. Conclusion

Agrivoltaics achieves what competing land-use models cannot: a genuine harmony between renewable energy production and sustainable agriculture. It is not a trade-off, not a compromise, but a documented, measurable synergy validated across climates, crop types, and economic contexts. The LER values of 1.3–1.84 recorded across global trials are, in essence, the quantified dividend of that harmony.

For India — a nation of 140 million farm holdings confronting simultaneous climate vulnerability, energy poverty, and the world's largest renewable energy ambition — agrivoltaics could be the key to achieving the **500 GW renewable target** without compromising food security. With the PM-KUSUM framework, state-level SKY schemes, the GIZ I-SUN partnership, and pioneering domestic projects demonstrating commercial viability, the institutional foundations for scale-up are in place. Agrivoltaics could indeed be India's key to achieving its 500 GW renewable energy target without compromising its food security.

The future of food and energy need not be a zero-sum competition for land. Agrivoltaics proves that with intelligent design, these twin imperatives can be synergistically integrated — turning the fields of today into the power stations and food gardens of tomorrow.

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Spine Gourd: Economic Significance, Utilization and Market Potential in Chhattisgarh

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Abstract

Spine gourd (*Momordica dioica* Roxb.), locally known as kakora or kantola, is a nutritionally rich and economically valuable underutilized vegetable crop predominantly found in the forested and tribal regions of Chhattisgarh. The crop is highly appreciated for its nutritional composition, medicinal properties, and seasonal market demand during the monsoon months. Collection and marketing of wild fruits provide an important source of supplementary income for tribal and rural households. Despite its significant commercial potential, large-scale cultivation remains limited due to the scarcity of quality planting material, inadequate production technologies, and low farmer awareness. Scientific cultivation, dissemination of improved varieties, efficient propagation techniques, and value-addition initiatives can enhance productivity, strengthen livelihood opportunities, and promote sustainable utilization of this indigenous vegetable crop.

Keywords: spine gourd, kakora, underutilized vegetable, tribal livelihood, market potential.

Introduction

Spine gourd (*Momordica dioica* Roxb.) is a perennial dioecious cucurbitaceous vegetable native to the Indian subcontinent and widely distributed across tropical and subtropical regions (Singh *et al.*, 2018). In Chhattisgarh, the crop occurs naturally in forests and wastelands and constitutes an important component of the traditional diet of tribal communities. Owing to its high nutritional value, medicinal importance, and adaptability to diverse agro-climatic conditions, spine gourd has attracted increasing attention as a promising crop for nutritional security and livelihood enhancement (Rashid *et al.*, 2020). However, its commercial cultivation remains limited because of inadequate domestication efforts, lack of improved varieties, and insufficient awareness regarding scientific production practices (Kumar *et al.*, 2022).

Economic Importance

Spine gourd contributes significantly to the rural economy of Chhattisgarh, particularly among tribal and forest-dependent households. Fruits harvested from natural habitats are sold in village and urban markets, generating seasonal income during the monsoon period (Yadav *et al.*, 2021). Owing to its limited availability and strong consumer demand, the crop often commands premium market prices compared with many conventional vegetables. Improved cultivars such as Indira Kankoda-1 and Chhattisgarh Kankoda-2 have demonstrated higher productivity and offer substantial opportunities for commercial cultivation (Kumar *et al.*, 2022). Expansion of cultivated area, coupled with improved production practices, can enhance farm profitability, generate employment, and strengthen livelihood security in rural areas (Pandey *et al.*, 2020).

Uses of Spine Gourd

Spine gourd is widely consumed as a vegetable, with its tender fruits used in a variety of traditional dishes. Unlike bitter gourd, its fruits are less bitter and more palatable, increasing consumer acceptance. In addition to fruits, young leaves, flowers, and seeds are also edible. The crop is rich in essential nutrients such as proteins, vitamins (notably vitamin C and carotene), minerals, and dietary fiber, thus contributing to nutritional security. Moreover, it possesses several medicinal properties and is traditionally used for treating ailments such as fever, diabetes, inflammation, and digestive disorders. Ethnomedicinal uses of spine gourd are well documented among tribal communities of central India (Singh *et al.*, 2018; Kumar *et al.*, 2022).

Demand in Chhattisgarh

The demand for spine gourd in Chhattisgarh is steadily increasing due to its unique taste, nutritional benefits, and seasonal availability. It is highly preferred during the monsoon season when it appears in local and urban markets. Urban consumers consider it a delicacy, which results in higher market prices. However, the supply is limited as most of the produce is collected from wild sources rather than cultivated systematically. This mismatch between demand and supply highlights the significant potential for expanding its cultivation and commercialization in the state (Kumar *et al.*, 2022).

Constraints and Opportunities

The cultivation of spine gourd faces several challenges, including its dioecious nature, low seed germination, difficulty in vegetative propagation, scarcity of quality planting material, and limited technical knowledge among farmers (Kumar *et al.*, 2022). Nevertheless, these constraints offer substantial opportunities for research and development. Introduction of improved varieties, standardization of propagation techniques, and promotion of scientific cultivation practices can significantly enhance productivity and profitability (Meena *et al.*, 2022). Furthermore, value addition, processing, and market-oriented production systems can increase farmers' income and improve livelihood security (Pandey *et al.*, 2020).

Conclusion

Spine gourd is a high-value indigenous vegetable with considerable potential for improving nutritional security, livelihood resilience, and sustainable agricultural development in Chhattisgarh. Its increasing market demand, premium pricing, and adaptability to local conditions make it an attractive enterprise for small and marginal farmers (Yadav *et al.*, 2021). Promotion of improved varieties, scientific cultivation techniques, quality planting material production, and value-addition interventions can facilitate wider adoption and commercialization (Kumar *et al.*, 2022). Strategic support through research, extension services, and market development initiatives will be essential for unlocking the full economic potential of this underutilized crop (Meena *et al.*, 2022).

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Advances in Organic Potato Farming: Biological Inputs, Crop Management and Certification Pathways

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Abstract

Organic potato farming is emerging as a sustainable agricultural approach due to increasing consumer demand for residue-free food, environmental concerns and the need for long-term soil health management. Potato is a highly nutrient-demanding crop and its successful cultivation under organic systems depends on efficient nutrient recycling, biological soil enhancement and eco-friendly pest management strategies. The present review highlights the major components of organic potato production, including the use of organic manures, biofertilizers, biopesticides, organic seed materials and sustainable agronomic practices. The study also discusses major production constraints such as nutrient deficiency, late blight incidence, weed infestation, limited availability of certified organic inputs and challenges associated with organic certification procedures. Furthermore, the role of certification systems such as NPOP and PGS-India in maintaining quality assurance and market credibility has been examined. Adoption of disease-resistant varieties, integrated biological management practices and farmer-oriented institutional support systems can significantly improve the productivity and profitability of organic potato farming. Organic potato cultivation, therefore, represents a promising pathway towards environmentally sustainable, economically viable and health-oriented agricultural development.

Keywords: Organic potato farming, Biofertilizers, Organic certification, Sustainable agriculture, Biopesticides.

Introduction

Potato (*Solanum tuberosum* L.) is one of the most important food crops worldwide and plays a significant role in ensuring food and nutritional security due to its high productivity and wide adaptability. In recent years, growing concerns regarding excessive use of synthetic fertilizers and pesticides, soil degradation, environmental pollution and food safety have accelerated the demand for organically produced agricultural commodities. Organic agriculture focuses on maintaining ecological balance through the use of natural inputs, biological nutrient cycling and environmentally safe crop protection measures. In potato cultivation, organic farming practices emphasize the use of compost, farmyard manure, green manures, biofertilizers and biological pest management approaches to sustain productivity while minimizing environmental impact. Organic potato production not only contributes to soil health improvement and biodiversity conservation but also offers premium market opportunities for farmers. However, potato is a nutrient-responsive and disease-prone crop, making its management under organic systems comparatively challenging. Problems such as lower initial yields, severe late blight incidence, weed management difficulties and high certification costs often restrict large-scale adoption of organic potato cultivation. Additionally, maintaining compliance with certification standards under systems such as the National Programme for Organic Production (NPOP) and Participatory Guarantee System (PGS-India) requires proper documentation, field monitoring and input verification. Despite these challenges, increasing awareness among consumers regarding chemical-free food and sustainable farming practices has created substantial opportunities for organic potato cultivation. Therefore, understanding the essential inputs, production practices, certification procedures, and major constraints associated with organic potato farming is necessary to develop efficient and sustainable production systems. This review aims to provide a comprehensive overview of organic potato cultivation, focusing on key inputs, agronomic practices, production challenges and certification pathways for sustainable crop production.

Essential Inputs for Organic Potato Cultivation

Organic potato production depends on the use of biological and eco-friendly inputs that improve soil fertility, nutrient availability and overall plant health. The following inputs play a major role in maintaining productivity under organic systems.

- **Organic Manures:** Organic manures such as farmyard manure (FYM), compost, vermicompost and green manure crops are important nutrient sources in organic potato cultivation. These materials improve soil structure, increase water-holding capacity and promote beneficial microbial activity in the soil. Vermicompost and compost also release nutrients slowly, ensuring a continuous nutrient supply throughout crop growth. Green manure crops such as dhaincha and sunhemp help in nitrogen fixation and organic matter addition, thereby improving long-term soil fertility (Reganold & Wachter, 2016).

- **Biofertilizers:** Biofertilizers such as Azotobacter, Azospirillum, phosphate-solubilizing bacteria (PSB) and potassium-solubilizing bacteria (KSB) enhance nutrient availability and uptake in potato crops. Azotobacter and Azospirillum contribute to biological nitrogen fixation, while PSB and KSB help in converting unavailable phosphorus and potassium into plant-available forms. These microbial inoculants also improve rhizosphere activity and reduce dependency on external nutrient inputs, thereby supporting sustainable potato production systems (Goffart et al., 2022).
- **Organic Micronutrient Sources:** Organic potato cultivation often requires supplementation of micronutrients through natural sources such as rock phosphate, bone meal, wood ash and bio-derived zinc chelates. Rock phosphate and bone meal are important phosphorus sources, while wood ash contributes potassium and calcium. Bio-derived micronutrient formulations help correct nutrient deficiencies without disturbing soil ecology. The balanced use of these inputs improves tuber quality, plant growth and resistance against environmental stress (Mattsson & Wallén, 2003).
- **Biopesticides and Botanicals:** Biopesticides and botanical products are widely used for pest and disease management in organic potato farming. Neem oil acts as an insect repellent and growth regulator for sucking pests such as aphids and whiteflies. Trichoderma species are effective against soil-borne fungal pathogens, while Beauveria bassiana and Bacillus subtilis help suppress insect pests and foliar diseases. These biological control agents reduce the environmental impact associated with chemical pesticides and support ecological balance in farming systems (Rana et al., 2020).
- **Organic Seed and Seed Treatments:** The use of certified organic seed is essential to maintain the integrity of organic production systems. Healthy and disease-free seed tubers minimize the spread of pathogens such as late blight and bacterial wilt. Seed treatment with biological agents such as Trichoderma and Pseudomonas fluorescens enhances disease resistance and improves seedling vigour. Proper seed selection and treatment also contribute to uniform crop establishment and higher marketable yield (Kumar et al., 2022).

Agronomic Practices

Organic potato cultivation requires the adoption of suitable agronomic practices that improve crop health and reduce pest and disease incidence.

- **Crop Rotation:** Crop rotation with legumes and non-host crops helps reduce pest and disease buildup in potato fields. Rotating potatoes with crops such as peas, beans and cereals interrupts the life cycle of soil-borne pathogens and improves soil nitrogen status through biological fixation. Crop diversification also improves soil biodiversity and reduces nutrient depletion (Reganold & Wachter, 2016).
- **Earthing Up, Mulching and Mechanical Weeding:** Earthing up is an important operation in potato cultivation that protects developing tubers from sunlight exposure and encourages tuber enlargement. Mulching with straw or crop residues conserves soil moisture, regulates soil temperature and suppresses weed growth. Mechanical weeding reduces weed competition without the use of synthetic herbicides and helps maintain clean cultivation in organic fields (Goffart et al., 2022).
- **Irrigation Management:** Proper irrigation scheduling is essential in organic potato farming to avoid excessive soil moisture that favours disease development. Moderate and well-timed irrigation ensures healthy tuber formation and reduces the occurrence of fungal diseases such as late blight. Efficient water management practices such as drip irrigation can further improve water-use efficiency and crop productivity (Timpanaro et al., 2021).
- **Soil Solarization and Resistant Varieties:** Soil solarization involves covering moist soil with transparent polyethylene sheets to increase soil temperature and suppress soil-borne pathogens, nematodes and weed seeds. The use of resistant potato varieties also plays a major role in reducing disease incidence under organic conditions. Combining resistant varieties with biological management strategies improves sustainability and reduces crop losses (Rana et al., 2020).

Challenges in Organic Potato Production

Despite its environmental and health benefits, organic potato cultivation faces several production and management challenges.

- **Lower Initial Yields:** Organic potato systems often experience lower yields during the conversion period because nutrients from organic sources become available slowly compared to synthetic fertilizers. Farmers may require several seasons to restore soil fertility and biological activity to optimum levels. This transition phase can affect profitability and discourage adoption among small farmers (Mattsson & Wallén, 2003).

- **Management of Late Blight:** Late blight caused by *Phytophthora infestans* is one of the most serious diseases affecting potato cultivation worldwide. Managing this disease in organic farming is difficult because the use of synthetic fungicides is restricted. Farmers depend mainly on resistant varieties, cultural practices and biological control measures, which may not always provide complete protection under favourable weather conditions (Rana et al., 2020).
- **Availability and Cost of Organic Inputs:** The limited availability and high cost of certified organic seeds, biofertilizers and biopesticides often restrict large-scale adoption of organic potato farming. In many regions, farmers face difficulties accessing quality inputs at the required time, which affects crop performance and productivity (Goffart et al., 2022).
- **Weed Management Challenges:** Weed management in organic systems requires greater labour input because chemical herbicides are prohibited. Frequent manual or mechanical weeding increases production costs and labour requirements. Uncontrolled weeds can compete with potato plants for nutrients, water and sunlight, thereby reducing tuber yield and quality (Kowalczyk, 2019).

Certification Barriers

Organic certification involves strict documentation, field inspections and traceability requirements. Small and marginal farmers often find the certification process complex, time-consuming and expensive. Lack of awareness and limited institutional support further constrain participation in certified organic markets (Amritpal & Sidhu, 2015).

Organic Certification Requirements

Certification ensures that organic potato production complies with established national standards.

- **NPOP and PGS-India Standards:** In India, organic certification is regulated through the National Programme for Organic Production (NPOP) and Participatory Guarantee System (PGS-India). These systems establish standards related to production practices, input use and record maintenance to ensure product authenticity and consumer trust.
- **Conversion Period:** Farmers are required to undergo a conversion period of approximately 2–3 years before produce can be certified as organic. During this phase, synthetic

fertilizers, pesticides and genetically modified inputs are prohibited. The conversion period helps restore soil ecology and eliminate residues of prohibited substances.

- **Record Keeping and Inspection:** Detailed record-keeping is mandatory for maintaining certification status. Farmers must document all farming operations, input applications and harvesting details. Certification agencies conduct periodic field inspections to verify compliance with organic standards and assess traceability measures.
- **Organic Labeling and Marketing:** After successful inspection and evaluation, farmers receive certification approval, allowing them to market their produce using the official organic logo. Certified organic potatoes often fetch premium prices due to increasing consumer demand for safe and environmentally friendly food products (Reganold & Wachter, 2016).

Conclusions

Organic potato cultivation has considerable potential for promoting sustainable agriculture, improving soil fertility and producing safe, high-quality food with reduced environmental impact. The successful adoption of organic production systems depends on the effective integration of organic nutrient sources, biofertilizers, biological pest management strategies and eco-friendly agronomic practices. Although organic potato farming faces several constraints, including lower productivity during the transition period, disease pressure, weed management challenges and certification complexities, these limitations can be minimized through improved research support, farmer training and institutional interventions.\n\nThe promotion of disease-resistant and nutrient-efficient potato varieties, expansion of quality organic input supply chains and strengthening of farmer cooperatives and FPOs can significantly improve adoption and profitability. Simplification of certification procedures and wider dissemination of digital monitoring and record-keeping technologies may further encourage small and marginal farmers to participate in organic markets. With increasing consumer preference for chemical-free and environmentally sustainable food products, organic potato farming offers strong future prospects for ecological sustainability, rural livelihood enhancement and climate-resilient agricultural development.

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Khet Bachao Abhiyan: India's Battle to Reclaim Its Farmlands

(A Nationwide Campaign to Heal the Soil, Empower Farmers, and Secure the Future of Indian Agriculture)

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Abstract

India's agricultural soils are under mounting stress from decades of excessive chemical fertiliser use, rising input costs, and import-dependent supply chains. In response, the Union Government launched the Khet Bachao Abhiyan — a nationwide month-long campaign (1–30 June 2026) spearheaded by Union Agriculture Minister Shivraj Singh Chouhan — to promote balanced fertiliser use, soil health management, and scientific farming practices at the grassroots level. Backed by ICAR's field outreach, Krishi Vigyan Kendras, and dashboard-based monitoring, the campaign has already engaged over 7 lakh farmers directly and reached 2.71 crore citizens. This article examines the campaign's objectives, institutional architecture, and its potential to catalyse a lasting shift in India's farm culture.

Introduction

India's fields have long been the backbone of its civilisation. From the fertile plains of the Gangetic belt to the black cotton soils of Vidarbha and the red laterite tracts of the Deccan, Indian farmland has fed billions for millennia. Yet today, those same fields are under siege — not from drought or flood alone, but from a quieter, more insidious enemy: the unchecked overuse of chemical fertilisers and pesticides that has been slowly poisoning the very soil that sustains us.

It is in this critical context that the Union Government launched the **Khet Bachao Abhiyan** — literally, the "Save the Field Campaign" — a month-long, nationwide initiative running from **1 June to 30 June 2026**, carrying the powerful clarion call: *"Save the Soil, Save Farming, Save Farmers."*

The Making of a Movement

The Khet Bachao Abhiyan was formally launched by **Union Minister for Agriculture and Farmers Welfare, Shri Shivraj Singh Chouhan**, from Ramsiya village in the Raisen district of

Madhya Pradesh on 1 June 2026. But its roots lie in a directive from the Prime Minister himself, who had called upon the nation to urgently address the rampant and indiscriminate use of chemical fertilisers that is degrading India's agricultural land.

Minister Chouhan, in his address at the launch, set the tone unequivocally: *"The direction of the campaign is quite clear — save the farms, manage the costs, improve the soil, make farmers aware, and develop a new culture of agricultural management at the village level."*

What distinguishes this campaign from past government initiatives is its insistence on being a **mass movement** rather than a bureaucratic exercise. Chouhan explicitly rejected the traditional top-down administrative model, instead ordering a collaborative framework that directly connects local Panchayats with state and central government machinery, ICAR institutions, Krishi Vigyan Kendras (KVKs), and agricultural universities.

Why Now? The Crisis Beneath Our Feet

The urgency of Khet Bachao Abhiyan cannot be overstated. Indian agriculture is navigating a perfect storm of challenges that have been decades in the making.

Soil Degradation at Alarming Scale: Decades of excessive nitrogen, phosphorus, and potassium application — far beyond what crops can absorb — have acidified soils, destroyed microbial communities, and depleted organic carbon content across vast swathes of farmland. The result is a paradox: farmers use more fertiliser every season, yet crop yields are plateauing or even declining in several states.

The Import Dependency Trap: India's fertiliser situation is acutely vulnerable to global disruptions. The country imports nearly 70% of its urea requirements and virtually 100% of its potash. As the ongoing West Asia crisis has disrupted international shipping routes, input costs have spiked sharply. The Khet Bachao Abhiyan is thus not merely an environmental initiative — it is a matter of national food security and economic resilience.

Mounting Farm Costs: The economics of Indian farming have turned punishing. Rising input costs — fertilisers, pesticides, fuel — are squeezing already thin margins, pushing millions of small and marginal farmers deeper into debt. Reducing wasteful chemical use is a direct, actionable route to bringing down the cost of cultivation.

Environmental Consequences: Excess fertiliser use has downstream consequences far beyond the farm gate. Nitrate contamination of groundwater, eutrophication of water bodies, and greenhouse gas emissions from agricultural soils are increasingly serious environmental concerns that demand immediate action.

What the Campaign Seeks to Achieve

The Khet Bachao Abhiyan is built around several interconnected pillars:

Balanced and Judicious Fertiliser Use: At the heart of the campaign is the promotion of soil test-based nutrient management. Farmers are being educated to apply fertilisers based on the actual needs of their specific soil — not by habit or guesswork. The Soil Health Card scheme, already operational across the country, is being given fresh momentum under this campaign.

Promotion of Natural and Organic Inputs: The campaign actively encourages farmers to adopt organic alternatives — green manures, bio-fertilisers, vermicompost, and crop residue incorporation — as supplements or substitutes to chemical inputs. Integrated Nutrient Management (INM) demonstrations are being conducted in farmers' fields to show, practically, how balanced nutrition improves both yield and soil health.

Awareness on Soil Health Cards: Farmers are being guided on how to obtain and interpret their Soil Health Cards and translate the recommendations into actionable changes in their fertiliser and amendment practices.

Identification of Counterfeit Inputs: A particularly valuable component of the campaign is training farmers to identify spurious and counterfeit fertilisers, seeds, and pesticides — a menace that causes enormous losses to farming households every year while further damaging soil and crop health.

Water Conservation and Crop Diversification: The campaign also emphasises water-efficient practices, crop selection suited to local agro-climatic conditions, and alternative farming strategies for regions prone to low or erratic rainfall.

ICAR's Role: Science Meets the Soil

A key institutional pillar of the Khet Bachao Abhiyan is the **Indian Council of Agricultural Research (ICAR)**, implemented under the Department of Agricultural Research and Education. ICAR's outreach achievements under the campaign have been remarkable.

As of mid-campaign, **12,979 awareness camps and seminars** have been conducted across the country, directly engaging approximately **7.17 lakh farmers** in scientific nutrient management and sustainable farming practices. Through digital and media outreach initiatives, the campaign has reached nearly **2.71 crore citizens** — a figure that underscores the scale and ambition of this initiative.

ICAR's network of Krishi Vigyan Kendras has been mobilised as the frontline of this campaign, with scientists and agricultural experts visiting villages to deliver practical, evidence-based demonstrations. The focus is on building farmers' confidence through real-world results — not pamphlets and platitudes.

A New Administrative Architecture

One of the most significant innovations of Khet Bachao Abhiyan is its **dashboard-based monitoring system**. Minister Chouhan directed that a detailed roadmap be prepared for every district, clearly mapping which officer, scientist, institution, or team would visit which village on which date. District-level programmes are planned well in advance, ensuring accountability at every level.

Central and state governments, ICAR, agricultural universities, and local Panchayats are all part of an integrated coordination network. The Minister himself has been personally active — reaching out to state Chief Ministers by phone and in writing, seeking their full cooperation in making the campaign a genuine national movement.

Farmers receive direct, personalised advice tailored to their local weather conditions, soil quality, water availability, and market scenarios — a significant departure from one-size-fits-all extension services of the past.

The Road Ahead: Building a New Farm Culture

Khet Bachao Abhiyan is, at its core, an attempt to fundamentally shift India's agricultural culture — away from the chemical-intensive model that took root after the Green Revolution, towards a more ecologically intelligent and economically sustainable approach.

The campaign's slogan — *Save the Soil, Save Farming, Save Farmers* — captures a profound truth: these three goals are inseparable. Healthy soil is the foundation of viable farming, and viable farming is the foundation of farmer welfare. There can be no lasting solution to the agrarian crisis that ignores the health of the land itself.

As the campaign enters its final weeks, its impact is already being felt. Thousands of village-level meetings have broken down complex soil science into practical guidance that farmers can act on immediately. Young agricultural graduates deployed as field volunteers are building bridges between laboratory knowledge and lived farming experience.

Whether Khet Bachao Abhiyan succeeds in catalysing a lasting transformation will depend on what happens after 30 June — whether the awareness translates into behavioural change, whether state governments embed its lessons into their regular extension services, and whether the political will demonstrated at the launch is sustained through the next sowing season and beyond.

But for now, India's farmlands have a message from their government: *your soil matters, your future matters, and this nation is paying attention.*

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