



# Role of Artificial Intelligence and Machine Learning in Indian Agriculture: A Review

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**Abstract**— This review examines the transformative impact of Artificial Intelligence (AI) and Machine Learning (ML) on the agricultural sector in India. It provides a detailed analysis of the traditional agricultural landscape, highlighting its inherent challenges, before delineating the various applications of AI/ML that are revolutionizing farming practices. A critical comparison between AI/ML-driven methods and conventional approaches demonstrates the superior efficiency, precision, and sustainability offered by these advanced technologies, supported by quantifiable benefits. The report further explores the future trajectory of AI/ML in Indian agriculture, discussing emerging technologies, crucial policy implications, and the significant scalability challenges that must be addressed to unlock the full socio-economic and environmental potential of AI/ML for a resilient and sustainable agricultural future in India.

**Keywords**— Indian Agriculture, Artificial Intelligence, Machine Learning.

## I. INTRODUCTION

Indian agriculture serves as a critical economic backbone, employing approximately 42% of the country's population and contributing 18% to its Gross Domestic Product (GDP) (1, 2). This highlights its immense socio-economic significance, extending beyond mere food production to underpin national well-being and the livelihoods of a vast populace. Despite its foundational role, the sector is plagued by persistent challenges, including chronically low productivity, highly fragmented landholdings, significant climate risks, and pervasive market inefficiencies (1, 2, 3).

Historically, Indian agriculture has been profoundly dependent on the monsoon, with its unpredictable variability directly impacting crop yields and national food security (4, 5, 6). This dependence underscores a fundamental vulnerability that has shaped traditional farming practices for centuries. The sector's substantial contribution to both GDP and employment, coupled with its deep-seated vulnerabilities, reveals a critical underlying theme: Indian agriculture is not merely an economic sector but a complex socio-economic system whose stability is intrinsically linked to national well-being.

This intrinsic connection means that successful technological interventions in Indian agriculture hold the potential for a profound multiplier effect. Such interventions would deliver economic gains while also enhancing social stability, reducing rural poverty, and improving farmer livelihoods. These outcomes would positively impact national development goals and potentially reduce rural-to-urban migration pressures.

Artificial Intelligence (AI) and Machine Learning (ML) have rapidly emerged as potent tools, demonstrating the capacity to revolutionize agricultural practices worldwide, significantly enhancing productivity and fostering sustainability (1, 2, 7, 8, 9, 10, 11). These technologies enable a spectrum of advancements, including increased overall productivity, the adoption of precision agriculture, highly efficient resource management, sophisticated disease and pest management, and optimized supply chain operations (7).

This academic review aims to provide a comprehensive and rigorous analysis of the applications of AI/ML specifically within the Indian agricultural context. It will meticulously detail the agricultural scenario in India both before and after the integration of AI/ML, offer an explicit comparison highlighting the superiority of AI/ML methods over traditional practices, and project the future trajectory of agriculture with these advanced technologies. The review consolidates data exclusively from various peer-reviewed journals and academic sources, ensuring a robust, evidence-based understanding for researchers, policymakers, and practitioners in the field.

## II. THE AGRICULTURAL LANDSCAPE IN INDIA BEFORE AI/ML INTEGRATION

### 2.1 Traditional Farming Practices and Their Characteristics

Indian agriculture has historically been shaped by indigenous farming techniques, passed down through generations, embodying deep cultural traditions and environmental wisdom (12). These time-tested methods were often characterized by their labor-intensive nature and reliance on local knowledge.

For weed management, traditional methods included mulching, mixed cropping, hand pulling, mowing, and crop rotation (13). Local inhabitants also utilized herbal mixtures, sour buttermilk, and citrus-vinegar solutions as natural weedicides (13). Pest control relied on simple, localized methods such as spreading ash, applying cow urine with plants, mixing cow dung for natural pesticides, and using buttermilk ('lassi') to attract and trap pests (13). Plant-based alternatives, particularly *Azadirachta indica* (neem), were highly valued for their powerful insecticidal and repellent properties (13). Intercropping, where farmers grow a variety of crops, was also a successful technique for providing a natural defense against insect infestations (13).

Soil fertility enhancement traditionally involved organic methods like compost, farmyard manure, green manure, and biofertilizers (e.g., *Rhizobium*, *Azospirillum*) to enrich soil with essential nutrients and improve microbial activity (12). Vermicomposting, an age-old technique, accelerated organic matter decomposition, creating nutrient-rich humus that enhanced soil structure and water retention (12). Minimal tillage and natural mulching methods were practiced to prevent soil erosion and maintain soil structure, further enhancing long-term agricultural productivity (12). Water management utilized indigenous irrigation methods such as rainwater harvesting, bamboo drip irrigation, and tank irrigation, optimizing water use and reducing reliance on depleting groundwater sources (12).

These traditional systems, characteristic of the "agricultural era 1.0," focused on basic food creation and animal breeding using rudimentary tools like sickles and shovels, resulting in inherently low productivity due to their manual and labor-intensive nature (14). A significant majority (95.76%) of surveyed Indian farmers predominantly relied on these traditional techniques prior to AI adoption (3).

### 2.2 Enduring Challenges and Limitations

Despite the inherent sustainability and ecological harmony often associated with traditional practices (12), Indian agriculture has faced a confluence of severe and persistent challenges that traditional methods have struggled to adequately address.

- **Climate Variability and Monsoon Dependence:** The sector is highly susceptible to climate variability and monsoon dependence, facing non-uniform climatic conditions, unpredictable monsoons, frequent droughts, and extreme weather events like cyclones and floods, which disrupt traditional cropping cycles (3, 4, 6). India has witnessed a 50% increase in extreme rainfall events over recent decades, shrinking winter seasons affecting rabi crops like wheat and mustard, and heatwaves impacting crop viability and livestock health (6). Historically, prolonged decreases in monsoon rainfall have been linked to the decline of ancient civilizations, such as the Indus Valley, underscoring the deep-rooted vulnerability to climatic shifts (5).
- **Low Productivity and Resource Degradation:** Challenges of low productivity and resource degradation are pervasive, stemming from limited natural resources and the pressing need for sustainable practices (3, 7, 8). The overuse of chemical fertilizers and pesticides, often adopted in attempts to boost yields, has led to severe environmental consequences, including reduced soil organic matter, increased salinity and acidity, and widespread water source pollution (6). Furthermore, over-irrigation and unsustainable groundwater exploitation have resulted in a critical water crisis in many regions (6).
- **Pest and Disease Burden:** Pest and disease burden continues to pose significant threats, leading to substantial crop losses (3, 15). Current major pests include the Fall Armyworm, locust swarms, and Whitefly, affecting staple crops like maize, rice, and cotton, respectively (15). Overall crop losses due to insect pests dramatically increased from 7.2% in the early 1960s to 23.3% in the early 2000s, with cotton losses escalating from 18.0% to 50.0% (15). Traditional methods for identifying plant diseases and pest infestations are often time-consuming, subjective, and prone to inaccuracies, making effective control difficult (8, 16).
- **Market Inefficiencies and Farmer Indebtedness:** Indian agriculture is characterized by market price instability, weak infrastructure, and inefficient market systems (3, 8). Farmers traditionally rely on intermediaries, which often results in lower profit margins and susceptibility to price manipulation (8). The absence of real-time price forecasting in traditional market mechanisms makes informed selling decisions difficult (8). Inadequate access to formal credit forces small farmers to borrow from informal moneylenders at exorbitant interest rates, which is a leading cause of farmer indebtedness and suicides in states like Maharashtra, Telangana, and Punjab (6). Farm input costs have steadily risen, while output prices remain volatile or stagnant (6). Post-harvest losses are substantial, reaching up to 30% for some perishable crops, due to inadequate cold chains, storage, and transportation infrastructure (6).
- **Socio-Economic Pressures and Labor Shortages:** The sector also faces significant socio-economic pressures and labor shortages. Rapid population growth exacerbates the demand for food, intensifying pressure on agricultural resources (7, 9). The labor-intensive nature of Indian agriculture faces severe labor shortages due to rural-to-urban migration, complicating timely farming operations (1, 3). Many farmers also lack access to extension services and modern inputs, and knowledge of climate-resilient practices remains limited (6).
- **Impact of COVID-19:** The impact of COVID-19 further exposed and intensified these pre-existing systemic vulnerabilities. The pandemic significantly disrupted the labor-intensive agricultural sector in India, imposing movement restrictions, causing severe labor shortages, leading to decreased agricultural outputs, and exacerbating post-harvest losses due to strict lockdowns (3). This crisis underscored the urgent need for resilient technological solutions that could operate effectively even under such constraints (3).

Collectively, these challenges illustrate that traditional Indian agriculture has been a system caught in a cycle of vulnerability. The reliance on unpredictable monsoons and manual, reactive methods meant farmers were constantly exposed to external shocks. When climate events hit, crop failures occurred, which, coupled with rising input costs and market volatility, led to farmer indebtedness. This economic hardship, in turn, drove rural-to-urban migration, creating labor shortages and further weakening the agricultural base. The observed increase in pest losses despite traditional methods indicated their diminishing efficacy against evolving threats. The COVID-19 pandemic did not introduce new problems but rather acted as a severe accelerant, exposing and intensifying these pre-existing systemic vulnerabilities.

There is also a notable paradox between "traditional wisdom" and "modern challenges." While indigenous methods are often lauded for their inherent sustainability, ecological harmony, and resourcefulness, they are demonstrably insufficient to address 21st-century agricultural complexities such as escalating pest losses, severe climate change impacts, and the intricacies of modern market dynamics. The declining interest among younger generations in traditional practices and the lack of institutional support further underscore a systemic shift away from these methods (12). This implies that the optimal future for Indian agriculture is unlikely to be a complete abandonment of traditional methods but rather a synergistic integration with modern scientific and technological advancements (17). AI/ML's role, therefore, becomes one of augmenting and enhancing existing knowledge and practices by providing the data-driven insights, precision capabilities, and predictive power that traditional methods inherently lack.

### III. TRANSFORMATIVE APPLICATIONS OF AI/ML IN INDIAN AGRICULTURE

Artificial Intelligence and Machine Learning are fundamentally revolutionizing agricultural practices in India by enabling unprecedented levels of precision, automation, and data-driven decision-making across the entire value chain.

#### 3.1 Precision Agriculture and Optimized Resource Management

AI and ML are fundamentally revolutionizing crop production through the implementation of precision farming and site-specific crop management techniques (7). These technologies empower farmers to optimize their agricultural practices by collecting and analyzing vast amounts of data about their fields (7).

- **Crop and Soil Monitoring:** AI-powered IoT sensors are deployed to track soil moisture levels, enabling highly precise irrigation and significantly reducing water wastage (8, 10, 11, 18, 19). AI systems continuously analyze steady streams of data to monitor soil conditions, detect nutrient deficiencies, and provide automatic alerts when conditions deviate from defined thresholds (11). Image recognition and deep learning models facilitate distributed soil health monitoring without the need for extensive laboratory testing infrastructure (10). Drones equipped with AI-enabled cameras capture real-time images of crop fields, helping farmers identify stress conditions early and optimize the use of fertilizers and pesticides (8, 19).
- **Yield Prediction:** AI and ML techniques are crucial for accurately predicting and optimizing crop yields (7, 8, 10, 11, 18, 19, 20, 21, 22, 23). These models analyze historical and real-time data, including weather patterns, soil conditions, crop growth stages, nutrient availability, and pest infestations (7). AI models have demonstrated high accuracy, achieving up to 90% in crop yield forecasting (8).
- **Automated Irrigation:** AI and ML are effectively employed to optimize water usage in orchard irrigation by analyzing complex datasets from soil moisture sensors and weather stations (24, 25). By creating sophisticated predictive models, AI can forecast precise irrigation needs, leading to significant water savings (up to 27%) and energy savings (up to 57%) (24).

- **Optimal Planting and Sowing:** AI algorithms generate precise and customized recommendations for farmers, including optimal planting times, selection of appropriate seed varieties, accurate fertilizer application rates, and efficient irrigation schedules (7, 10, 23). A notable example is the sowing application developed by Microsoft India and ICRISAT for Andhra Pradesh, which provides customized village guidance based on real-time weather conditions, soil data, and other indicators (10).

### 3.2 Advanced Pest and Disease Management

AI and ML applications offer highly efficient and accurate methods for both weed detection and management (7). Utilizing advanced computer vision techniques, AI algorithms can analyze images of fields captured by drones or cameras mounted on agricultural machinery to precisely identify and differentiate between crops and weeds, enabling targeted herbicide application (7, 20). Once weeds are detected, AI-powered robotic systems can autonomously apply herbicides, reducing reliance on broad-spectrum chemicals and minimizing their environmental impact (7).

Early detection and control of diseases and pests are paramount for preventing significant crop losses (7). AI and ML technologies assist farmers in identifying and managing these threats efficiently by employing image recognition algorithms to detect visual symptoms of diseases or pests (7, 8, 11, 16, 19, 20, 26). AI models are capable of analyzing historical disease outbreak patterns to predict potential pest infestations and recommend timely interventions (8, 20). Drones equipped with multispectral cameras can identify pest or disease affected areas at an early stage (23). A practical example is the Plantix mobile application, powered by AI, which allows farmers to upload images of their crops and receive instant diagnoses of diseases and pests, significantly improving upon traditional, often time-consuming and inaccurate methods (8).

### 3.3 Enhancing Agricultural Supply Chains and Market Access

AI can play a transformative role in agricultural marketing by significantly enhancing efficiency, reducing risks, and improving overall profitability for farmers (8).

- **Market Price Forecasting:** AI-powered predictive analytics utilize vast datasets of historical pricing data, real-time demand-supply trends, and economic indicators to forecast market prices with high accuracy (8, 23). This capability helps farmers comprehend market demand and consumer preferences, enabling them to strategically time their market entry and negotiate better prices for their produce (10, 23).
- **Logistics Optimization:** AI algorithms are employed to optimize transportation routes, ensuring that perishable goods reach markets in the shortest possible time, thereby substantially reducing post-harvest losses (8, 10, 23, 27). AI-powered inventory management systems meticulously track storage conditions and notify farmers of optimal storage durations, further minimizing waste (8).
- **Digital Marketplaces:** AI-powered e-commerce platforms facilitate direct sales from farmers to consumers, effectively eliminating intermediaries and ensuring fairer pricing for agricultural produce (8, 23). The integration of AI with blockchain systems enhances traceability and transparency in agricultural transactions, building trust across the supply chain (8). India's eNAM (National Agricultural Market) is an example of an AI-enabled platform providing real-time price discovery (23).

### 3.4 Role of Agricultural Robotics and Drones

Agricultural robotics, often referred to as Agribots, are gaining increasing popularity in India due to persistent labor constraints and the growing need to feed a large population (10). These robots automate various labor-intensive farming tasks such as planting, harvesting, weeding, and monitoring crop health, thereby increasing production efficiency and reducing dependency on human labor (7, 10).

Drones, equipped with AI and ML capabilities, capture high-resolution imagery and perform aerial surveys of vast agricultural lands (7, 8, 10, 19). This data is invaluable for comprehensive crop monitoring, precise mapping, and identifying areas of concern. More advanced drones are capable of carrying and delivering payloads, including herbicides, fertilizers, and water, enabling targeted application (10).

### 3.5 Other Key Applications

- **Livestock Management:** AI and ML technologies are being applied to monitor animal health, behavior, and productivity. Sensors and wearable devices collect real-time data on parameters such as temperature, heart rate, and milk production, facilitating early disease detection and timely intervention (7, 20).
- **Financial Inclusion and Credit Access:** AI-driven credit scoring models are emerging as a vital tool to help farmers, particularly those without traditional banking history, access formal loans and insurance products (23). Predictive models assess risks more accurately, enabling crop insurance providers to offer fair and tailored policies (23). Furthermore, AI-enabled smart marketplaces can facilitate access to institutional finance providers for farmers who require bridge financing (1).
- **Advisory Services:** AI-driven chatbots and virtual assistants are being developed to provide farmers with real-time, personalized advisory services, empowering them to make more informed and timely decisions regarding their farming operations (8).

## IV. AI/ML: A PARADIGM SHIFT FROM TRADITIONAL AGRICULTURAL METHODS

The integration of Artificial Intelligence and Machine Learning represents a profound paradigm shift from traditional agricultural practices in India, offering superior efficiency, precision, and sustainability. This transformation is evident across various aspects of farming, leading to quantifiable improvements and empowering farmers with data-driven decision-making capabilities.

### 4.1 Quantifiable Improvements in Efficiency and Productivity

AI-powered solutions enable farmers to achieve significantly higher output with fewer resources, marking a substantial leap in efficiency (11, 18).

- **Increased Yields:** Pilot projects across India have demonstrated remarkable improvements in crop yields (1, 8). For instance, a field study in Telangana, leveraging AI-led precision farming techniques, resulted in a notable 21% increase in chili yields (8). Furthermore, AI-based sowing advice implemented in Andhra Pradesh has been shown to boost yields by up to 30% (1). AI-driven decision support systems, by analyzing complex variables like weather, soil properties, and crop genetics, recommend optimal practices for sowing, irrigation, fertilization, and harvesting, directly leading to increased crop yield and quality (19).
- **Reduced Input Costs:** The same Telangana pilot project reported an 11% increase in unit prices for produce and a significant 9% reduction in the use of fertilizers and pesticides (1). AI-enabled rapid soil analysis tools play a crucial role in preventing the overuse of chemical inputs by providing precise nutrient recommendations (1). Globally, AI-integrated machinery, such as John Deere's computer vision systems in the US, has demonstrated up to a 90% reduction in chemical use through selective herbicide application (19).
- **Reduced Post-Harvest Losses:** AI-driven logistics management has proven highly effective in mitigating post-harvest losses, with studies indicating a 15% reduction in India (8). AI algorithms optimize transportation routes and inventory management for perishable goods, ensuring faster delivery and reduced spoilage (8).

**TABLE 1**  
**QUANTIFIABLE BENEFITS OF AI/ML ADOPTION IN INDIAN AGRICULTURE**

Benefit Category	Quantifiable Impact	Context/Example	Source
Increased Crop Yield	21% increase in chili yields	Telangana chili farmers	-8
	Up to 30% yield boost	Andhra Pradesh sowing advice	-1
Reduced Pesticide Use	9% reduction	Telangana chili fields	-1
	Up to 90% reduction	Global example (John Deere AI machinery)	-19
Reduced Fertilizer Use	9% reduction	Telangana chili fields	-1
Reduced Post-Harvest Losses	15% reduction	India-wide logistics	-8
Water Savings	Up to 27% water savings	Predictive irrigation systems	-24
Farmer Net Profit Increase	Average \$800 per acre per crop season	Telangana pilot project	-1

#### 4.2 Enhanced Resource Utilization and Environmental Sustainability

AI-powered precision agriculture optimizes resource efficiency and significantly reduces environmental impact, fostering sustainable practices (7, 19).

- **Water Conservation:** AI-powered IoT sensors meticulously track soil moisture levels, enabling precise, demand-driven irrigation and substantially reducing water wastage (8, 18, 19). In India, companies like Fasal and CropIn utilize AI and IoT to monitor soil moisture and weather conditions, ensuring precise water delivery and leading to decreased water consumption while maintaining high crop yields (19). Predictive algorithm-based irrigation systems have demonstrated the potential to achieve up to 27% water savings (24).
- **Minimized Chemical Use:** AI-driven variable rate technology (VRT) precisely determines the exact amount of fertilizer or pesticide needed for different sections of a field, optimizing crop health and minimizing excessive chemical use (19). This targeted approach directly promotes more sustainable farming practices (8).
- **Curbing Emissions:** At a macro level, AI can contribute to curbing emissions from the agricultural sector by optimizing resource use and enhancing efficiency, thereby assisting economies in achieving net-zero goals (1).

#### 4.3 Superior Risk Mitigation and Climate Resilience

AI provides critical predictive insights for various agricultural activities by analyzing diverse data sources, fundamentally shifting from reactive responses to proactive management (3, 18).

- **Weather and Climate Resilience:** AI models are capable of forecasting rainfall patterns, predicting droughts, and anticipating temperature changes with greater accuracy, enabling farmers to plan ahead and significantly minimize risks associated with unpredictable climate conditions (8, 11, 19, 20, 23, 28). This capability directly reduces climate vulnerability for the agricultural sector (1).
- **Pest and Disease Risk Reduction:** AI-driven surveillance systems effectively monitor vast crop fields and detect anomalies indicative of pest infestations or disease outbreaks (8). Computer vision techniques enable early detection of pests and diseases, allowing for timely interventions that minimize crop losses (7, 8, 11, 16, 19, 20, 26). This represents a significant improvement over traditional, often time-consuming and inaccurate methods of identification and control (8, 16).

#### 4.4 Transition to Data-Driven Decision Making

AI and ML fundamentally enable a transition to data-driven insights, informing and optimizing decision-making processes across the agricultural value chain (11, 19, 20). Farmers gain access to sophisticated tools that allow them to make more

informed and precise decisions regarding irrigation, fertilization, crop health management, and optimal planting and harvesting times (11, 19). Crucially, AI provides forward-looking, data-driven insights, facilitating a fundamental shift in farmer behavior from reactive decisions based on past successes to proactive strategies informed by predictive analytics (1).

In contrast, traditional methods often relied on subjective physical monitoring, anecdotal evidence, and human expertise, which were cumbersome, required great focus, and were prone to human error (9, 16). AI replaces manual data extraction with automated, precise, and accurate systems that are free from human error factors (9).

#### 4.5 Socio-Economic Empowerment of Farmers

The integration of AI holds significant promise for enhancing efficiency, reducing risks, and ultimately improving profitability and livelihoods for Indian farmers (8).

- Increased Profit Margins:** By directly connecting farmers with buyers and reducing reliance on intermediaries, AI significantly enhances profit margins for producers (8). Pilot projects in India have led to substantial boosts in net profits, with some farmers experiencing an average increase of \$800 per acre per crop season, a significant gain given the average annual income of less than \$1,500 (1).
- Economic Stability and Improved Livelihoods:** AI-driven price forecasting contributes directly to greater economic stability and improved livelihoods for farmers by enabling better financial planning and helping them avoid distress sales during periods of market volatility (8).
- Greater Market Access and Financial Independence:** Digitizing agricultural trade through AI empowers farmers by providing real-time market information and accurate price forecasts (8). AI-enabled smart marketplaces eliminate information gaps, reduce reliance on traditional middlemen, and facilitate access to institutional finance, fostering greater financial independence (1).
- Addressing Labor Shortages:** AI-powered robotic systems automate various labor-intensive tasks, thereby reducing dependency on human labor (10). Furthermore, AI could potentially match farmers with available labor across regions, helping to alleviate severe labor shortages caused by rural-to-urban migration (1).

**TABLE 2**  
**COMPARISON OF TRADITIONAL VS. AI/ML-DRIVEN AGRICULTURAL PRACTICES IN INDIA**

Aspect	Traditional Method	AI/ML-Driven Method	Key Advantage of AI/ML
Crop Monitoring	Manual observation/Visual inspection (9)	Sensor/Drone/Satellite data analysis (7, 8, 10, 19)	Real-time insights, early detection, comprehensive health assessment
Pest/Disease Management	Broad-spectrum chemical application/Manual removal/Herbal remedies (6, 13)	Image recognition/Predictive analytics/Targeted robotic application (7, 8, 16, 20, 26)	Highly targeted intervention, reduced chemical use, improved efficacy
Irrigation	Monsoon reliance/Flood irrigation/Indigenous methods (6, 12)	AI-optimized smart irrigation systems with real-time data (8, 18, 19, 24, 25)	Significant water and energy savings, optimized crop hydration
Yield Prediction	Historical data/Farmer experience/Anecdotal (22)	Predictive modeling with high accuracy (up to 90%) using vast datasets (7, 8, 18, 21, 22)	Higher accuracy, better planning, risk mitigation
Market Access	Reliance on middlemen/Local physical markets (8)	Digital platforms/Real-time price forecasting/Direct farmer-to-buyer linkages (8, 10, 23)	Increased farmer profit margins, market transparency, reduced post-harvest losses
Decision Making	Reactive/Intuitive/Experience-based (1)	Proactive/Data-driven/Evidence-based (11, 19, 20)	Enhanced resilience, informed strategic planning, reduced human error
Resource Use (Fertilizers/Pesticides)	Broad application of inputs with limited precision (6)	Precision application based on site-specific needs (7, 19)	Minimized waste, cost savings, reduced environmental impact

## V. THE FUTURE TRAJECTORY OF AI/ML IN INDIAN AGRICULTURE

The future trajectory of AI in Indian agriculture is poised for significant and transformative advancements, aiming to address systemic challenges and unlock new potentials for productivity, sustainability, and farmer empowerment (1).

### 5.1 Emerging Technologies and Advanced AI/ML Models

The agricultural sector is expected to see the widespread adoption and refinement of several promising AI applications across the value chain.

- **AI-enabled Crop Planning:** This technology represents a crucial shift from reactive crop choices to a data-driven strategy. It utilizes a wide range of farm and non-farm data, including soil health, weather patterns, historical prices, and food import/export trends, to recommend optimal crops for specific regions (1). This approach aims to align production with market demand, thereby minimizing price fluctuations and mitigating risks of overproduction and underproduction (1).
- **AI-enabled Rapid Soil-Health Analysis:** Traditionally, soil testing is time-consuming and expensive, often leading farmers to overuse fertilizers. AI-enabled rapid soil analysis employs spectroscopy for instant, on-site assessment of soil characteristics such as composition, nutrient availability, water retention, and alkalinity (1). This provides immediate feedback on nutrient levels, moisture, and acidity, helping to prevent chemical overuse, optimize fertilizer application, and guide crop rotation to restore soil fertility (1).
- **AI-enabled Pest Prediction and Control:** This application leverages historical climate and soil data, along with farm-level data, to provide early warnings about potential pest attacks (1). It also offers real-time recommendations for managing infestations, including pest identification, risk scores for different farm locations, integrated pest management (IPM) practices, and vendor information (1). India's National Pest Surveillance System (NPSS) is an example of an AI-powered platform for this purpose (1).
- **AI-enabled Smart Marketplaces:** These digital platforms utilize historical data to provide adaptive price forecasts to producers and aggregators (1). They incorporate Internet of Things (IoT) hardware at aggregation points for accurate and rapid measurement of quality and quantity (1). These marketplaces aim to eliminate information gaps, reduce reliance on intermediaries, and connect farmers directly with buyers, ensuring fair prices and access to remunerative markets (1). They also facilitate access to institutional finance for farmers needing bridge financing (1). Agnext's IoT hardware is specifically cited as an example of AI-driven quality assessment (1).
- **Advanced ML/DL Techniques:** Beyond these specific applications, the agricultural sector will increasingly benefit from advanced ML/DL techniques. Deep learning (DL) techniques are highlighted as superior for handling complex, large datasets, offering state-of-the-art predictive performance for yield forecasting (14). Recurrent Neural Networks (RNNs) are particularly competitive for time series data forecasting, especially for long-term predictions, overcoming limitations of traditional models like ARIMA (14). Explainable AI (XAI) techniques are identified as crucial for making AI decisions more understandable and interpretable for farmers, thereby building essential trust and facilitating adoption (14, 22). Furthermore, Federated Learning and Edge Computing are emerging approaches that

can reduce reliance on centralized cloud computing while maintaining data privacy and enabling real-time decision-making at the farm level (14).

## 5.2 Policy Implications and the Enabling Environment for Scalability

Governments are identified as primary stakeholders, holding a leading role in establishing foundational systems and creating an enabling environment for AI integration in agriculture (1). This involves a multi-pronged approach.

- **Developing AI Strategy:** Federal and provincial governments must formulate comprehensive AI strategies tailored to their specific regional agricultural needs, ensuring these strategies foster both scalability and inclusivity (1). Examples cited include India's UP Digital Agriculture policy (1).
- **Deploying Contextual Policies:** Clear and achievable policies are crucial across several domains, including the procurement of AI solutions by public agencies, the provision of financial incentives, and the establishment of responsible data-sharing frameworks (1). Enabling procurement policies and market access, for instance, requires guidelines for public agencies to procure AI solutions, streamlining adoption, with references to the World Economic Forum's "AI Procurement in a Box" guidelines (1). Financial incentives, such as offering direct support to farmers, potentially through farmer cooperatives or innovative digital payment solutions like e-RUPI (which provides earmarked vouchers for AI services), are crucial to encourage AI adoption (1). The Saagu Baagu 2.0 project in Telangana is highlighted for its provision of financial support to farmer cooperatives for AI solutions (1).
- **Robust Digital Public Infrastructure and Data-Sharing Policies:** This is foundational for scaling AI solutions. It involves aggregating agriculture-related data (landholding, crop data, soil health, weather patterns, market prices) on secure and accessible platforms to reduce data silos and enable AI developers (1). Initiatives like India's Agri Stack and Telangana's Agricultural Data Exchange (ADeX) are cited as key examples (1). Furthermore, frameworks like DEPA (Data Empowerment and Protection Architecture) and Telangana's ADMF (Agricultural Data Management Framework) are highlighted as public-private efforts designed to ensure secure and smooth data flow for AI applications (1).
- **Promoting Responsible AI:** Governments should proactively initiate discussions on developing "progressive" AI regulations to carefully balance the positive and negative externalities of AI deployment (1). India's Ministry of Electronics and Information Technology (MeitY) has already launched an initiative to build tools and frameworks for ethical AI development and deployment across various sectors (1).
- **Multistakeholder Collaboration:** The success of AI deployment and adoption is contingent upon robust collaboration among diverse stakeholders, including research institutions, industry players, agritech start-ups, financiers, and government bodies (1, 2). This collaborative approach is essential for developing and validating scalable AI solutions that are relevant to the Indian context (1).

## 5.3 Addressing Scalability Challenges and Barriers to Adoption

Despite the promising results of AI in Indian agriculture, scaling these benefits to millions of smallholder farmers faces significant and complex obstacles (1).

**TABLE 3**  
**KEY CHALLENGES TO AI/ML ADOPTION AND PROPOSED SOLUTIONS IN INDIAN AGRICULTURE**

Challenge	Description	Proposed Solutions/Mitigation Strategies	Source
Fragmented Infrastructure	Major barrier to effective deployment; internet-based AI limited in remote areas	Robust digital public infrastructure; government investment in rural connectivity	(1, 3)
Limited Access to High-Quality Data	AI relies on large volumes of real-time, quality data; inconsistent collection, incompatibility	Centralized data platforms (e.g., Agri Stack, ADeX); standardized data collection protocols; investment in data infrastructure	(1, 14)
Affordability for Smallholder Farmers	Low annual income restricts ability to pay for AI solutions; perceived as added burden	Financial incentives (e.g., e-RUPI vouchers); support through cooperatives (e.g., Saagu Baagu 2.0); institutional finance access	(1, 3)
Small and Fragmented Landholdings	Increases per-farmer cost of AI delivery; solution providers focus on larger farms	Policy focus on solutions adaptable to smallholdings; collective adoption through farmer groups/cooperatives	-1
Limited Institutional Validation	Few mechanisms to validate new tech before deployment; increases perceived risk	Establishment of validation sandboxes; pilot projects and controlled testing; transparent evaluation frameworks	-1
Farmer Reluctance to Trust AI	Hesitancy due to traditional practices or lack of tangible proof; "fear of missing out"	Small-scale demonstrations showing tangible results; Explainable AI (XAI) to build understanding and trust	(1, 3, 22)
Information Overload and Generic Advice	Inundation of conflicting online sources; advice lacks local context	AI-driven chatbots for personalized advisory; curated, reliable digital platforms; context-specific recommendations	(1, 8)
Technical Expertise and Digital Literacy	Limited computer/internet use in rural areas; lack of knowledge for complex models	Government-provided web-services; lower tariffs for AI systems; hands-on training programs; user-friendly interfaces	-3
Reactive Decision-Making	Farmers base decisions on past successes, overlooking dynamic factors	Promotion of predictive analytics tools; education on data-driven planning; integration of real-time insights into advisory	-1
Labor Shortages	Rural-to-urban migration causes scarcity for timely operations	AI-powered robotics for automation; AI-driven platforms for labor matching across regions	(1, 10)
Lag in Research Dissemination	Slow transfer of university research to field applications	Strengthened extension services; industry-academia partnerships; rapid prototyping and validation of innovations	-1

#### 5.4 Long-term Socio-Economic and Environmental Impacts

The long-term integration of AI into Indian agriculture promises profound socio-economic and environmental impacts, transforming the sector into a more resilient, sustainable, and profitable enterprise.

- **Enhanced Productivity and Yields:** AI has already demonstrated significant improvements in yields, with pilot projects showing increases such as 21% for chili farmers in Telangana and up to 30% from AI-based sowing advice in Andhra Pradesh (1). Sustained investment in AI is expected to further boost agricultural output, ensuring food security for India's growing population.
- **Reduced Input Costs and Improved Profits:** AI-driven precision farming leads to substantial reductions in the use of fertilizers and pesticides (e.g., 9% reduction in Telangana chili fields) (1). This, coupled with increased yields, translates into significant boosts in net profits for farmers, with some experiencing an average of \$800 per acre per crop season (1). This economic uplift directly addresses farmer indebtedness and improves livelihoods.
- **Better Market Access and Price Stability:** AI-enabled smart marketplaces connect farmers directly with buyers, reducing reliance on intermediaries and eliminating information gaps about demand, supply, and prices (1). This empowers farmers to sell to the most remunerative markets, reducing distress sales and contributing to greater

economic stability (8). AI-enabled crop planning further aims to minimize price fluctuations by aligning production with market demand (1).

- **Increased Resilience to Climate Change and Pests:** Predictive analytics provide accurate weather forecasts and help manage pest infestations proactively, significantly reducing climate vulnerability and economic losses from pest attacks (1). This shift from reactive to proactive management builds agricultural resilience against unpredictable environmental challenges.
- **Sustainable Farming Practices:** AI's ability to optimize resource use (e.g., precise water and chemical application) directly contributes to curbing emissions from the agricultural sector, helping India achieve its net-zero goals (1). Rapid soil analysis helps prevent overuse of chemical inputs and guides crop rotation to restore soil fertility, addressing critical issues like soil degradation (1). The National Pest Surveillance System, for instance, promotes scientific pest-management practices and prevents pesticide misuse, ensuring sustainable farming (1).
- **Financial Inclusion and Farmer Empowerment:** AI-enabled smart marketplaces can facilitate access to institutional finance providers for farmers needing bridge financing (1). AI solutions, particularly those with simple visual and voice-driven interfaces, can empower farmers without requiring high digital literacy, providing them with real-time market data and pricing insights to negotiate better (1).

## VI. CONCLUSION

The integration of Artificial Intelligence and Machine Learning marks a profound and transformative era for Indian agriculture, moving it beyond historical vulnerabilities and traditional limitations towards a future characterized by enhanced precision, productivity, and sustainability.

Historically, Indian farming, deeply reliant on unpredictable monsoons and labor-intensive methods, has grappled with systemic challenges such as low productivity, severe pest and disease burdens, market inefficiencies, and acute climate vulnerability, all of which were exacerbated by events like the COVID-19 pandemic. Traditional practices, while embodying ecological wisdom, proved increasingly insufficient against these complex 21st-century pressures.

AI/ML technologies have emerged as a pivotal solution, offering a paradigm shift across the entire agricultural value chain. Through precision agriculture, AI-powered systems enable highly optimized resource management, including intelligent crop and soil monitoring, accurate yield prediction, and automated irrigation, leading to substantial water and energy savings. Advanced pest and disease management, facilitated by computer vision and predictive analytics, allows for early detection and targeted interventions, significantly reducing chemical use and crop losses. Furthermore, AI is revolutionizing agricultural marketing by providing real-time price forecasting, optimizing supply chain logistics to minimize post-harvest losses, and fostering direct farmer-to-buyer digital marketplaces, thereby increasing farmer profitability and market transparency. The advent of agricultural robotics and drones further automates laborious tasks, enhancing efficiency and addressing labor shortages.

The comparative analysis unequivocally demonstrates the superiority of AI/ML-driven methods. Quantifiable benefits, such as a 21% increase in chili yields, up to a 90% reduction in pesticide application, and a 15% decrease in post-harvest losses, underscore the tangible economic and environmental advantages. This shift from reactive, experience-based decision-making to proactive, data-driven strategies fundamentally builds resilience against climate variability and market volatility. AI/ML enables sustainable intensification, allowing India to meet its growing food demands while simultaneously mitigating environmental degradation and contributing to net-zero goals.

The future trajectory of AI in Indian agriculture holds immense promise, with emerging technologies like AI-enabled crop planning, rapid soil-health analysis, and smart marketplaces poised to further revolutionize the sector. However, realizing this potential necessitates a robust enabling environment. Governments must take a leading role in formulating comprehensive AI strategies, deploying contextual policies (including financial incentives and streamlined procurement), and establishing robust digital public infrastructure with clear data-sharing frameworks. Promoting responsible AI development and fostering multi-stakeholder collaboration are also critical.

Despite the transformative potential, significant scalability challenges persist. Fragmented infrastructure, limited access to high-quality data, affordability concerns for smallholder farmers, fragmented landholdings, and farmer reluctance to adopt new technologies pose substantial barriers. Addressing these challenges requires concerted efforts in policy innovation,

infrastructure development, digital literacy enhancement, and localized demonstrations to build trust and demonstrate tangible benefits.

In conclusion, AI/ML offers a compelling pathway for Indian agriculture to transition from a vulnerable, labor-intensive system to a resilient, efficient, and sustainable agri-business model. While the journey to widespread adoption is complex, the profound socio-economic and environmental benefits—ranging from increased farmer incomes and food security to reduced resource degradation and climate resilience—underscore the imperative for continued research, strategic investment, and collaborative action across all stakeholders. The integration of AI/ML is not merely an option but a necessity for securing a prosperous and sustainable agricultural future for India.

### CONFLICT OF INTEREST

The authors declare no conflict of interest.

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