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AI-Enabled Sustainable Agriculture through Smart Sensing Systems in India

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ABSTRACT:

Agricultural production systems worldwide are confronted with the challenge of meeting growing demand due to rising population, urbanisation, changing diets, and increased consumption of animal-based food and processed goods, while ensuring environmental sustainability through enhanced resource-use efficiency. Current agricultural production systems and food-supply chains are recognised as inefficient and unsustainable—causing severe environmental impacts and threatening the well-being of all earthlings—since the resources consumed are disproportionately high compared to the food and non-food products produced. Similar challenges exist in the edible-food-supply chain of production and catering. Numerous factors, such as climate change, soil infertility, and low fertiliser-promotion efficiency pose adverse impacts on the efficiency of agricultural food production and food-supply chains (Min et al., 2023). Emerging artificial-intelligence technologies may enhance resource-use efficiency, food systems, and various other aspects of food production, processing, logistics, and consumption along the edible-food-supply chain (Chowdhury et al., 2023).

Keywords: Agricultural, Indian Economy. Demography, Sustainable Agriculture, artificial-intelligence

1. Introduction

As economies develop, there is growing need for sustainable agricultural systems and practices to ensure the continuous supply of food, fodder, fuel, and raw materials. However, global warming and limited resources have not only exacerbated food insecurity but also affected existing systems. AI applications that monitor irrigation, cultivate crops, forecast outputs, and assess climate data can support sustainable agriculture while minimizing resource wastage. Smart sensing systems that detect soil moisture, crop health, and nearby meteorological conditions help optimize irrigation, pest control, and crop planning. However, they rely on robust, scalable systems to collect, transmit, and analyze data. Architecture based on sensor networks, edge-fog-cloud computing, and fusion-driven databases facilitate smart sensing in agriculture. Sensor networks gather diverse data from the field and send it to edge devices that filter, pre-process, and transmit it to cloud servers for further processing. Computation offloaded to the edge reduces latency, traffic, and energy consumption, while fog nodes complement edge devices. Data fusion aggregates multi-modal data to derive insights, localize targets, and identify trends, enabling non-linear models for precision agriculture, improving reliability and augmenting archiving of historic datasets (Mitra et al., 2022) ; (Min et al., 2023).

2. Thematic Foundations

Sustainable agriculture seeks to enhance productivity and profitability while improving the economy and living standards of farmers, and safeguarding resources for future generations. Sustainable agricultural practices comprise a crop- and region-specific set of management practices that include efficient irrigation and fertilizer application, integrated pest management, adoption of high-yielding varieties, strengthening of cooperatives, better access to markets, and the preservation of indigenous crop species. Some agricultural interventions, both technological and managerial, have been shown to improve the agricultural income of Indian farmers without compromising the sustainability of agriculture (Mitra et al., 2022).

India is presently one of the world's largest producers of farm produce (including paddy, wheat, pulses, cotton, fruits, and vegetables), and growth in the agriculture sector is increasingly driven by productivity improvements rather than area expansion. Artificial Intelligence (AI) is recognized as the fourth Industrial Revolution and has enormous potential to catalyze the digitization of agriculture. Digital technology harnesses data to provide useful farm advisory services. AI-enabled crop advisory covers a wide range of services such as weather forecasting, soil testing, pest and disease forecasting, nutrient management, and irrigation scheduling. Smart sensing technologies such as IoT (Internet of Things) devices, drones, and mobile devices serve as important enablers of the AI-enabled digital transformation of agriculture. Such smart sensing technologies gather real-time and near-real-time data on a variety of agricultural parameters that can then be processed by digital platforms to provide relevant and timely advice to the farmer. Smart drones can be used for precision spraying of pesticides and nutrients. Smart farming services based on data collected by smart sensor systems have the potential to provide wide-ranging benefits to Indian agriculture (R. Shoaib et al., 2023).

2.1. Principles of Sustainable Agriculture

Sustainable agriculture aims to produce food and textile fibers in a way that satisfies the evolving needs of society without compromising the ability of future generations to meet their own needs. Sustainable agriculture is therefore a multidimensional concept. To cite only a few of the dimensions considered important by different societies, it should, 1) conserve soil and water resources, 2) protect the environment, 3) ensure food security, 4) enhance livestock welfare, and 5) make farming a financially viable occupation (Pacceli Reis da Fonseca et al., 2019).

In sustainable agriculture, crop watering, choices of agrochemicals to be applied, and food-purchase decisions are driven by public sensory monitoring of dew and rain accumulations, soil moisture levels, and satellite and weather-station data on variegated meteorological conditions along with historical and real-time price data on different food commodities (P Wani et al., 2016). Tailored advice on future watering and selection of agro-chemicals such as fertilizers, herbicides, and pesticides is provided through mobile connectivity. Routine inputs for different food-purchase advisories also consider position of the consumer with respect to nearby food-seller addresses. Ecosystem- and supply-chain-level water and carbon foot-print information is shared through the same media (Mitra et al., 2022).

2.2. Role of Artificial Intelligence in Agriculture

Agricultural practices and systems are faced with multiple challenges such as rising operational costs, labour shortages, poor profit margins, increasing impacts and uncertainties due to climate change, and incessant pressure on natural resources arising from mushroom population and indiscriminate urbanisation (Min et al., 2023). These challenges can only be mitigated via precision and smart agriculture system which is based on 5-0's: 0 missed operation, 0 offset time, 0 blind operation, 0 shortage and 0 pollution of productions.

Agricultural intelligence using big data analytics coupled with active and passive intelligence gathered through sensors and environment monitors enhances Crop Smart Agriculture technologies. Coupled with other intelligent solutions Crop Smart Agriculture further accelerates productive technology development and production coordination in agriculture plant factories, greenhouses and aquaculture facilities (Chen et al., 2023).

2.3. Smart Sensing Technologies: Definitions and Scope

Stakeholders are widely exploring the benefits of using artificial intelligence (AI) in agriculture. Geertjan Kooistra—the former Chief Innovation Officer of Wageningen University (the Netherlands)—indicates that AI can revolutionize food production systems and significantly reduce agriculture's environmental footprint. Kooistra also mentions that there are massive investments in research on AI for horticulture, permanent crops, livestock, and aquaculture. These initiatives aim to increase farm output, reduce agrochemical use, minimize labour costs, and decrease food waste—while ensuring food quality and safety. The agricultural value chain is leveraged by developing models and data-driven decision tools, which promote farm sustainability and enhance societal knowledge of agricultural systems (Pratim Bhuyan et al., 2021). Other innovations advancing the digital transformation of agricultural systems include robotics (e.g., automated harvesters and drones), satellites, biotechnology, genetic modification, mineral fertilisers, and seed treatment (Mitra et al., 2022).

Smart sensing refers to data collection and processing methodologies for better understanding of physical phenomena, along with decision-making based on premade associatives and conclusions. Atmospheric, environmental, and other conditions can be monitored through smart sensing technologies, which can improve efficiencies across multiple applications. Scope and definitions for smart sensing, smart sensing technologies, and smart agriculture are evolving, with ongoing research and innovations. Smart agriculture and smart agriculture technologies do not yet adhere to a universally accepted definition. Smart agriculture is often described as the application of information and communication technologies to provide information-services to agriculture stakeholders, which then allows inquiries, analyses, monitoring, and forecasts for better management or usage.

3. Contextual Landscape in India

India accounts for about 17% of the world population, 18% of livestock and 4% of forests. It has the world's largest number of farms (around 140 million) with an average farm size of 1.08 ha (less than 1 ha for around 86% of the farms). Agriculture contributes ~15% to GDP and engages ~50% of the workforce. However, the growth rate of the agricultural sector is lower (~2%), creating pressure on the farmers' income and living standards, which leads to unsustainable practices. India receives around 100 cm of annual precipitation; however, only 50% is harnessed. Around 50% of the irrigated area is through inefficient flood irrigation system, leading to wastage of water, energy and fertilizers. About 21% of crop yield is lost post-harvest due to poor storage, marketing and processing practices. Policy and institutional interventions are required to improve the growth rate of the agricultural sector, crop productivity, livelihood of farmers and reduction in food wastage. Digital technology via local and remote sensing is expected to help by providing data on crop, soil, weather, market price, pest and diseases to take informed decisions (P Wani et al., 2016).

3.1. Agricultural Demography and Trends

Agriculture is the mainstay for the Indian economy, contributing about ₹35 lakh crore (US $525 billion, 16-17% of Gross value added (GVA)), of which ₹15 lakh crore (US $220 billion, 7-8%) is from food and non-food crops (P Wani et al., 2016) and employing 58% of the workforce. Approximately 50% is supplied through large-, medium- and small-size farmers (landholdings >1ha), 20% through marginal farmers (landholdings between 0.1 to 1.0 ha) and 30% through landless farmers. India ranks first in pulse and jute production, second in rice, wheat, sugarcane, cotton, groundnut and fruit, third in vegetable and fourth in tea production (Grieve et al., 2019). Farmers face challenges such as costly quality inputs and precision farming technology, uncontrolled pest attack, soil health deterioration, limited access of quality seeds and fertilizers, knowledge gaps and market linkage. The rising population and growing demand for resources exert pressure on agriculture. Smart agriculture aids in improving productivity with optimum utilization of inputs and major issues addressed by smart agriculture are soil health, variety of seed selection, fertilizer and water managements, weed management and online market linkage are discussed in a holistic approach in smart agriculture concept towards sustainable development.

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3.2. Resource Constraints and Environmental Challenges

Driven by an increasing global population and the challenges posed by climate change, rising resource constraints are impeding agricultural sustainability (Grieve et al., 2019). Indian food production needs to rise by about 100 million tonnes by 2030 to meet domestic demand. Crop losses due to pests and pathogens are estimated at nearly 20% (Proctor, 2021). The Indian agricultural and allied sector is the largest employer in the country, and around 97 % farmers are smallholder farmers, but ONU-FAO estimates suggest two-thirds of smallholder farmers cannot meet their household food needs without vital crop and livestock supplements (UNESCO, 2022). Although national food production is increasing, numerous states in India still suffer from depleting water resources while 31 million hectares are affected by soil degradation (Proctor, 2021). Crop residues and waste generated by the meat, dairy and fishery industries continue to pollute soil and water Hirpara, 2021.

3.3. Policy and Institutional Frameworks

The National Policy for Farmers 2007, the Agricultural Technology Management Agency, the National Mission for Sustainable Agriculture, the Pradhan Mantri Krishi Sinchai Yojana, the National Policy on E-Governance in Agriculture, Digital India, and State ICT Policies and Policy on Computerization of Agriculture Cooperative Societies (P Wani et al., 2016) provide an enabling framework for the application of smart sensing technologies for sustainable agriculture in India (Min et al., 2023). India is heavily investing in employing information and communication technologies (ICTs) for 1) improving biophysical soil properties and soil health; 2) improving market connectivity for enhancing agriculture; and 3) Minimizing waste and adopting environment-friendly technology from production till marketing to boost net revenue of farm output. Through Mission India for Transforming Agriculture (MITrA), seven consortia comprising various national and international development agencies, NGOs, research institutions, and private partner(s) have been formed to address the diverse problems in the agriculture sector.

4. AI-Driven Sensing Architectures

Smart sensing systems for sustainable agriculture in India enhance productivity, optimize resource utilization, and minimize environmental impacts. AI-based architectures constitute a critical enabler for smart-sensing applications. Key features include sensor networks for distributed measurements and data aggregation; edge-fog-cloud computing paradigms for resource-efficient data storage, transmission, analysis, and management; and data-analytics techniques that facilitate sensor-driven decision-making.

Sensor networks enable a range of environmental parameters (e.g., temperature, humidity, soil moisture, vibration) to be measured simultaneously at different locations while addressing the need for data aggregation and preprocessing prior to transmission (Mitra et al., 2022). An AI-driven sensing architecture comprising temperature, humidity, soil moisture, and ultrasonic sensors has been proposed to support controlled irrigation in tea plantations. Embedded controllers run a threshold-based ruleset that switches pumps on or off in responses to sensor readings. A mobile app delivers notifications and enables remote pump control.

Fog and edge computing facilitate distributed data analysis in the vicinity of the sensors, alleviating transmission-load and latency requirements associated with cloud-only solutions. Such paradigms enable timely detection of critical events (e.g., high soil moisture, equipment failure) and faster feedback to actuator controls (Alzuhair & Alghaihab, 2023). A sensor-driven irrigation-management system collects soil-moisture, rain, temperature, humidity, and pH data at the farm level. The data is first analysed at the peripheral that regulates local actuators, with periodic aggregation uploaded to the cloud. A similar approach has been proposed for the monitoring of irrigation events and equipment health in greenhouses.

Data-fusion techniques aggregate information inputs from multiple sensors to derive higher-level indicators for decision support. A machine-learning-based wireless-sensor-network framework generates irrigation recommendations by analysing soil-pH, moisture, salinity, and temperature data received from multiple monitoring stations.

4.1. Sensor Networks and Data Aggregation

Sensor networks play a fundamental role in precision agriculture, performing continuous monitoring of soil nutrients, pest populations, and environmental conditions to support effective farming decisions. A wireless sensor network consists of spatially distributed autonomous nodes equipped with sensors, a micro-controller, a radio transceiver, an antenna, and a power unit. Each node collects data on various parameters such as soil moisture, temperature, humidity, and light intensity, communicates the collected data to gateway nodes, and passes along qualified information toward the sink (Shafi et al., 2019).

Effective irrigation requires significant investments and is vital to agricultural performance and productivity in regions with limited rainfall. For this reason, irrigation is often chosen based on forecasted precipitation within short or medium timeframes—the forecast period extending from several hours to one or two days—instead of information from months beforehand. Being a temporal and spatially variant phenomenon, crop development stages are the main variables that influence irrigation. Soil surface exploration focuses on determining the effective garden diameter of selected crop varieties in order to set up a regional irrigation scheduling model (Panchard et al., 2009).

A water shortage media monitoring system supports a water shortage monitoring service that takes the media sector as the target customer. The essential questions answered are: What water source is considered to satisfy the users' quality standard, and when is the water shortage likely to take place? These questions can also be adapted to solve faucet control and water-saving demands. In this case study, soil moisture measurement plus air temperature and relative humidity monitoring serve as the driver and constraint variables for modelling the water shortage scenario.

4.2. Edge, Fog, and Cloud Computing Paradigms

A typical smart agriculture architecture is comprised of the sensing layer, communication layer, computing layer, and data service layer. With relevant sensors, a sensing node can monitor environmental parameters (e.g., temperature, humidity, soil moisture, light, and pH) and send the acquired raw measurements to the edge or fog node. This edge or fog node aggregates inputs from multiple sensing nodes within the same area and sends the results to the final storage or cloud for complex analytics. Although the messages are shortened and fewer times sent over the network, the requirement is still significant for large-scale deployments (Stamatescu et al., 2019).

4.3. Data Fusion and Sensor-Driven Decision Support

Agriculture is a data-rich field. Utilization of sensing technologies generates a multitude of heterogeneous data, which require data fusion for effective processing and analysis to extract useful knowledge. A smart sensing system improves the accuracy of measurement of agricultural data by employing machine-learning techniques on the acquired data. The developed framework, deployed on cloud, Fog and edge computer architecture, collects sensing data and recommends suitable agricultural strategies to the farmer accordingly (Raj Vincent et al., 2019). Data from environmental sensing stations or devices is transmitted to a central computer unit for processing. Artificial Intelligence (AI) is the most effective technology to customize data collection and select the right algorithms for different applications (Min et al., 2023).

5. Applications in Indian Agriculture

Agriculture is an integral part of India's diverse economy and rural livelihood support system. Precision agriculture refers to a farming system which consistently crops to maximize crop yield, cut production cost and protects the environment by using high technology. The 21st century precision agriculture has evolved considerably on the basis of information technology. In India, there is less awareness of precision farming. Agriculture sector provides substantial employment, since the majority of rural sector population resides in villages. Indian agriculture depends on many crops, since world famous heavy monsoon also provide about 25 million hectare of waterlogged memosphere for paddy cultivation. An approach using crop data and applying LPS to attain higher yield output by artists working at India has been installed. This application uses academics for informal farming, to boost crop yield and also sustain for the upcoming generation (Chowdhury et al., 2023).

An efficient pest management at low cost can be assure by this application, which target pest variants of different crops and provide information about chemicals which can be used to deter (Wu et al., 2023).

5.1. Precision Irrigation and Moisture Management

Agriculture in India significantly depends on water resources, with monsoons often being inadequate. Efficient irrigation management is essential to conserve water and ensure appropriate plant growth. Accurate measurement of soil moisture content is crucial for proper irrigation scheduling, yet traditional methods are time-consuming and less precise. Moisture-sensing systems accelerated automatic soil-moisture detection by comparing readings against the gravimetric method. An accompanying irrigation system stops the water supply when moisture exceeds 80% and sends alerts via GSM when it drops below 50% ((Ugale) Dipak et al., 2018). Enhanced agricultural technology helps to reduce waste and improve efficiency.

Water consumption under reinforcement learning is lower than that of threshold-based and fixed scheduling methods. Effective agricultural irrigation management is vital for addressing freshwater shortages. Wireless sensor and internet technologies enable site-specific variable-rate irrigation, yet the approach remains underexploited. A learning-based control method supports online or offline training with a neural-network infrastructure for rapid development. A smart irrigation system at USDA's Conservation and Production Research Laboratory in Texas tests AI and IoT-based automated techniques. It collects real-time soil-moisture data from wireless sensors, integrates weather forecasts, determines optimal actions to maximise economic return, and executes precise irrigation across diverse terrains and conditions. The system permits manual operation or access via a web interface for programming, monitoring, and intervention (Sun, 2019).

Water management is critical for the agricultural sector's economic viability. Water-saving strategies and technological innovations are increasing in response to social, economic, and climate challenges. Low-cost sensors for irrigation management and monitoring have been developed to measure soil moisture and temperature, leaf water stress, water salinity, turbidity, and weather conditions. Advances in sensors, wireless networks, and IoT technologies are enhancing smart irrigation capabilities and enabling fertilisation optimisation (García et al., 2020).

5.2. Crop Health Monitoring and Pest Detection

Frequent monitoring of crop health and pest detection is necessary to prevent damage and ensure agricultural sustainability. The agriculture sector suffers a cumulative loss of around ₹153,000 crore annually due to pest and disease attacks (Adhikari et al., 2021). Sensors can monitor crop health (e.g., temperature, humidity, precipitation) and soil quality (e.g., moisture, pH, electrical conductivity), allowing early detection and prevention of attacks (Blanco-Carmona et al., 2023). Pest and disease outbreak levels can be predicted through decision tree algorithms, which estimate severity based on other observed variables. When the defined threshold is reached, information is conveyed to farmers via email, text, or multimedia messaging. Such early warnings minimize crop loss.

5.3. Fertilizer Management and Nutrient Optimization

In India, intelligent agriculture technologies can also improve fertilizer management and nutrient optimization. To date, much research on AI applications in plant nutrition concerns nutrient detection and the prediction of nutrient availability. Accurate soil and plant nutrient diagnosis is critical for optimizing fertilizer input while avoiding application costs and deleterious environmental impacts (A. Sheela et al., 2019). Fertilizer applications may represent India’s greatest fertilizer wastage, with up to 50 percent applied in excess of agronomic needs (P Wani et al., 2015). Weather forecasts and their impact on soil moisture also strongly influence fertilizer recommendation.

A Smart Cultivation project aims to address these limitations by developing an automatic fertilizer-irrigation control and management system to improve soil fertility and crop productivity. Soil nutrients, humidity, and temperature are monitored with sensors and transmitted to an Arduino Nano. Based on plant needs, the system then opens the appropriate valves to apply the prescribed quantities of fertilizer and water. By enhancing soil porosity and supplying necessary nutrients, the system increases crop yields. Fertigation, the combined application of irrigation and fertilizer, is a popular trend in indoor, greenhouse, and field farming spanning diverse crops, including vegetables, fruits, and ornamentals.

5.4. Yield Forecasting and Weather Resilience

Yield forecast models utilizing climatic, weather, and soil parameters, along with remote sensing data on healthy plantation growth, serve to enable timely harvesting and enhance logistical performance. Due to shortcomings of previous models, a pipeline was devised for multiple-crop yield estimation, predicting before germination based solely on precipitation, temperature, and soil moisture. The pipeline's neural network framework predicts yield distribution parameters and exceeds state-of-the-art scores in dataset-limited conditions. Weather forecasts, used with the pipeline, can predict potential yields for any time before sowing (Luiz de Freitas Cunha & Silva, 2020). Temperature and precipitation forecasts alone can moreover yield nationwide crop-level forecasts before the season starts, with satisfactory accuracy. Crop price forecasts allow formulation of optimal cropping portfolios beforehand (Gaddam et al., 2022).

6. Challenges and Risks

The adoption of AI-enabled smart sensing systems in Indian agriculture encounters a series of challenges and risks which may hinder widespread implementation. Technical barriers persist regarding the optimal design of suites of sensor types and deployment configurations, integration with legacy infrastructure, the operation and maintenance of extensive sensor networks, and the provision of reliable, high-bandwidth connectivity for data transfer. Appropriate considerations must also be given to data governance, ownership, privacy, and security, given the sensitive nature of data generated through these systems. Other critical concerns arise around technology access and the distribution of benefits across socioeconomic strata, as the agriculture sector incorporates a disproportionate number of smallholder farmers and workers. The rapid uptake of AI-enabled sensing systems may exacerbate existing inequalities if an informal sector of service providers does not arise to address the needs of marginalised constituents (Grieve et al., 2019) ; (Chowdhury et al., 2023).

6.1. Technical and Infrastructure Barriers

AI adoption requires ambient sensing and near-real-time use of data to produce best-practice guidelines suitable for diverse farming systems. India lacks an infrastructure of basic weather stations and other platform measures for crop, soil, and microclimate monitoring. India cannot afford to follow the natural growth of AI in Western countries that favour large-scale, industrial, capital-intensive farming. Smart remote monitoring systems can complement the nation's strategy for inclusive growth based on smallholder agriculture and bottom-up empowerment.

Formal AI-based labelling mechanisms are too expensive; preliminary requirements include low-cost, rugged sensors, sampling strategies resilient to seasonal and inter-annual variability, and, crucially, climatic data without connected equipment. Smallholder farming is a social process subject to software technology shifts. AI solutions successful in Western countries have failed to deliver quantifiable crop, yield, or income dividends in India. Predicted farm mechanisation and digitalisation for crop monitoring overseen by connected machinery have not occurred. AI-ready platforms incorporating government-distributed low-cost sensors have not emerged, suggesting investments would detract from deployment in other sectors.

6.2. Data Governance, Privacy, and Security

India lacks a comprehensive framework for data sharing in agriculture. Decisions are made at individual or local levels, resulting in fragmentation, inconsistencies, and missed opportunities for dissemination, conservation, and building public goods. Data-sharing policies must be tailored to the national, state, or local level, depending on information sensitivity. Such frameworks should be guided by principles of equity, nondiscrimination, relevance, and public good. Shared data must be public interest-oriented, promote collective monitoring and adaptation, and respect rights over locally generated inputs (Ryan et al., 2019).

Big Data governance in Indian agriculture considers a wide variety of issues. Fundamental concerns include the organization of rights and responsibilities among individuals, communities, and organizations; rules shaping the governance of evolving public goods; provisions that encompass exchange within areas classified as private; and regulations concentrating on protection and custody, particularly for vulnerable populations (Kotal et al., 2023).

6.3. Socioeconomic and Equity Considerations

Anticipated shifts in climatic zones and extreme weather are likely to threaten yields across many crops; more frequent rainfall, water logging, and flooding could specifically reduce yields for rice, soybean, maize, groundnut, and pigeon pea; saline stress may progressively challenge rice, cotton, sugarcane, and maize; and chill unit deficits may threaten crops such as mango, orange, and apple (P Wani et al., 2016). Crop-dependent advisory models enabling timely agronomic decisions can clarify management solutions. Both long-term forecasting models identifying rainy and dry weeks two months in advance and short-term forecasting models predicting optical airborne dust, thermal inversions, and dewpoint temperature three weeks in advance represent promising models needing further validation. Remote sensing data offers critical inputs for pest incidence models, and diverse measures exist for enhancing pest-related advisory capacity.

Qualitative inquiries involving 1000+ farmers reveal a large information gap for these pest and yield forecasting models across large farmer populations (Zelalem Bayih et al., 2022). International examples demonstrate the strong potential for precision farming, agricultural meteorology, and pest management advisory services to deliver value vis-à-vis input costs; such tools thereby warrant attention in the Indian context.

7. Case Studies and Pilot Initiatives

Sensing systems have been adopted in a number of pilot projects and studies across various regions in India. Examples included here reflect different sensing technologies, objectives, and practices adopted; results are not always rigorously documented.

A pilot project in high-density horticulture in Haryana deployed a wireless sensor network on a tomato farm. An outlier anomaly-detection algorithm examined irrigation data, and recommended to turn a valve on or off accordingly—yielding significant water savings, enhancing fruit size, and improving marketing prices (P Wani et al., 2016).

Data from a 12-year project on a 6-ha study plot (part of ICAR–NIAW) analysed total production compared with that in adjacent areas without these inputs. The purpose was to assess the impact of an AI-based sensor network to monitor soil, crop, and weather parameters. Also undertaken, but not fully analysed, were (i) a pilot project in Haryana using wireless sensors to monitor moisture content in Basmati paddy and (ii) soil health monitoring for sugar-cane crops in North Karnataka and Maharashtra (Shafi et al., 2019).

7.1. Regional Implementations and Outcomes

Big-data-based intelligence-embedded technologies fostered through the World Economic Forum's initiative may enhance policy on climate adaptation and resilience in underdeveloped regions of India, guided by participatory and engaged learning (P Wani et al., 2016). In Tamil Nadu, Ravi Kumar and Gopu overview at least 10 precision farming schemes promoted by agricultural universities, the Tamil Nadu Agricultural University (TNAU), and the government. Various centralized and decentralized sensors, decision-support systems, and telecommunication technologies underscore the importance of local knowledge for successful technology adoption. Readiness levels for adoption of space-based inputs index growth of the state's farming systems (R. Ravikumar Ramamoorthy & Jagan Gopu A, 2016).

7.2. Lessons Learned and Best Practices

Inherent diversity characterizes India's agriculture, formally segmented into broad categories according to inherent features relating to soil, climate, crop, transaction, etc. Initiatives need a comprehensive understanding of regional profiles, differences between rain-fed and irrigated systems, crop combinations, etc., along with mapping access to sensors, service providers, and partners (Neranjan Thilakarathne et al., 2022). Flexibility for big data analytics including climate predictions grants the ability to tailor recommendations to the system and choice of products. For instance, the availability of sensors targeting fruit/livestock/soil moisture and analytics to deploy forecasts provides far-reaching advantage (Garg et al., 2021).

An analytics platform accessible through a mobile interface, permitting off-line interaction ensures continuity. Limited technical abilities seldom impede usage as recommendations for rainfall plastic are common (P Wani et al., 2016). Combining large amounts of information presents challenges; very few datasets exist to draw upon. Collection of data from CSMCRI satisfactorily augments the available portfolio. Access to reliable market prices empowers decision making at all levels. Options include direct outreach to wholesale crowd sourced prices. Population density and language differentials necessitate phonetic and audio features linked with text.

8. Policy Implications and Pathways for Scaling

Strategic adoption of AI-driven, smart sensing approaches can be accelerated through coordinated actions on the engagement of policy-relevant stakeholders. Agriculture is driving large-scale shifts in Indian population distribution, contributing both to economic growth and environmental crises, while current climate projections paint a daunting picture of the future. Over the last two decades, policymakers and private enterprises have intensified initiatives to advance the adoption of digital technologies in agriculture. The resulting policies, investments, and research, development and innovation interventions respond to changing demographics, include both digital and agricultural activities, and are already underway.

However, current activity is not broad enough in scope, the coverage of existing policies remains fragmented and heterogeneous across states, and much of India still lacks the incentives, resources, skills, infrastructure, and technological capabilities to embrace engagement opportunities. To address these gaps, India needs to reconsider its approach to digital agriculture. Many countries, including developed economies and emerging market economies, rely on such an approach. At a strategic level, this can focus limited resources on a select number of digital technologies that are both scalable and compatible with the Indian agricultural system (P Wani et al., 2016). Much global attention is currently on AI. Such systems are now widely available and relatively inexpensive, while smart sensing driven by AI fits well with and complements many currently established practices and agricultural materials.

By prioritising the digital strategy and the smart-sensing-to-AI pathway, India can therefore increase the multifunctionality, durability, scalability, and resilience of its engagements in agriculture. Within this framework, action can address the interconnected opportunities and constraints and the growing need to co-operate across multiple settings that characterise the adoption of smart sensing driven by AI technologies in Indian agriculture today (Chowdhury et al., 2023). Efforts on each of these can receive further assistance through sharpening the scope of engagement, raising awareness, practical demonstration, building mutual understanding, shaping incentives, creating synergies, improving human capabilities, enhancing platforms and advancing standards.

9. Future Research Directions

Artificial Intelligence is playing an immense role in sustainable vertical farming by facilitating technology advancement, innovative farming strategy development, and environmental-conscious practice promotion. Further evolution of AI-based smart vertical farming management systems is essential for equipment automation and technique optimization. Research on smart innovations, including hydroponics, nutrient film technique, deep learning, image processing, spectral analysis, and the Internet of Things, warrants attention. Development of disease detection, soil health monitoring, nutrient management, crop optimization, and other automated and scalable decision-making systems employing machine learning continues to be crucial. Establishing clear threshold values for urban environment parameters forms the basis for managing temperature, humidity, and carbon dioxide concentration and promoting enhanced cubic production in cities. Design of sustainable digital twins, multi-environment versus single-environment selection of suitable use cases, urban cultivation technique consideration, and integration of big data from supply chains significantly contribute to sustainable smart vertical farming. Exploration of approaches for indoor environment control and designs for cultivating city-typical crops in productive urban agriculture constitutes the frontier of sustainable smart vertical farming. (Chowdhury et al., 2023)

10. Conclusion

AI can significantly contribute to India's sustainability goals and climate resilience (P Wani et al., 2016) , yet is presently underutilized. AI-driven solutions in natural and agricultural sciences encounter numerous technological and institutional barriers (Mitra et al., 2022). These challenges warrant careful examination of data governance and scalable design-implementation-integrated policy approaches (Chowdhury et al., 2023). AI coverage may be misinterpreted as an endorsement of the precautionary principle, which, while cautioning against changelessness in the face of uncertainty, nevertheless encourages a test-and-learn approach. Nevertheless, AI, like any other technology, is not a panacea for India's agricultural sector.

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