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Review on Future digital transforming technologies in agriculture in India: An integrated approach

Srikanthnaik J

Research Scholar, M.Tech in Farm Machinery and Power Engineering Division of Agricultural Engineering, ICAR- Indian Agricultural Research Institute, Pusa, New Delhi, India

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Corresponding Author: Srikanthnaik J

Abstract

The Indian agricultural sector, a cornerstone of its economy and food security, stands at a critical juncture requiring profound modernization to meet the escalating demands of a growing population and effectively address the multifaceted challenges of resource depletion, environmental degradation, and the intensifying impacts of climate change. This comprehensive review paper meticulously examines the ongoing and projected future landscape of digital transformation within Indian agriculture, a paradigm shift frequently termed Agriculture 4.0 or smart agriculture. It provides an in-depth overview of the pivotal role of a spectrum of emerging and converging technologies, including the Internet of Things (IoT), sophisticated and context-aware advanced sensor systems, cutting-edge Artificial Intelligence (AI), powerful Machine Learning (ML) algorithms, versatile robotics and automation solutions, advanced Unmanned Aerial Vehicles (UAVs) equipped with sophisticated payloads, robust big data analytics platforms, scalable and secure cloud computing infrastructure, and the potentially transformative distributed ledger technology of blockchain, in fundamentally revolutionizing traditional farming practices across the entire agricultural value chain. The paper critically analyzes the significant potential of these integrated technologies to substantially enhance agricultural productivity, optimize the efficient utilization of increasingly scarce resources, improve the accuracy and timeliness of decision-making processes at all levels, effectively mitigate a wide range of risks associated with agricultural production and market volatility, foster environmental sustainability and resilience, and ultimately meet the evolving and increasingly stringent consumer demands for enhanced food safety, improved nutritional quality, and transparent provenance. Furthermore, this review delves into the architectural framework of these integrated smart agricultural systems, emphasizing the critical necessity of robust collaborative efforts among diverse stakeholders, proactive and supportive policy frameworks from governmental bodies, strategic investments in crucial infrastructure development, and targeted initiatives to address significant challenges such as digital literacy gaps and ensuring the security and privacy of agricultural data. The ultimate goal is to pave the way for the widespread adoption and successful implementation of these transformative technologies, thereby securing a sustainable and prosperous future for Indian agriculture.

Keywords: Digital agriculture, agriculture 4.0, smart agriculture, precision farming, integrated agricultural system, internet of things, artificial intelligence, machine learning, robotics, unmanned aerial vehicles, big data analytics, cloud computing, blockchain, digital twins, quantum computing, India

1. Introduction

1.1 The Digital Revolution Imperative in Indian Agriculture

Agriculture in India, the very bedrock of its socio-economic fabric and a primary determinant of national food security, is currently navigating a critical transformative phase. This profound shift is being driven by the increasing and strategically vital convergence of traditional agricultural practices with the pervasive and enabling power of information and communication technology (ICT). This synergistic integration signifies a crucial new development with the overarching aim of achieving substantial and sustainable optimization of efficiency across the entirety of the agricultural value chain, seamlessly encompassing all critical stages from primary production and efficient distribution to informed consumption patterns. This dynamically evolving system can be accurately and comprehensively described as an integrated agricultural system, where the fundamental principles of comprehensive

digitization, sophisticated data processing and analysis, advanced digital control machinery, secure and seamless data transmission and collection networks, robust and reliable network infrastructure, and the intelligent automation of a wide range of agricultural activities are recognized as key and indispensable components (Tang, 2002) ^[17]. The contemporary agricultural landscape is increasingly and profoundly influenced by the strategic synergy of a diverse array of advanced technologies, including information technology (IT), biotechnology (BT), environmental technology (ET), and the revolutionary potential of nanotechnology (NT) (Hwang, 2002) ^[18]. The primary and multifaceted focus of this integrated approach extends beyond merely increasing yields to encompass critical objectives such as achieving significant and sustainable cost reduction at the fundamental production level, effectively alleviating the often-arduous physical labor burdens associated with traditional farming practices, consistently promoting the adoption of high-quality and

environmentally sustainable organic production methodologies, and establishing and rigorously enforcing stringent quality management protocols across all agricultural facilities and processes. Furthermore, a particularly critical aspect of this transformation is proactively addressing the evolving and increasingly sophisticated needs and expectations of consumers by establishing transparent, reliable, and secure systems that guarantee and deliver comprehensive and easily accessible food safety information, building trust and ensuring accountability. This necessitates the expanded and strategic application of IT across a wide range of agricultural farming automation systems and the intelligent introduction of advanced IT-driven distribution technologies, including the secure and efficient convergence of distribution data, at the crucial processing and distribution stages of the value chain. These interconnected and mutually reinforcing elements represent the fundamental building blocks in the creation of a truly comprehensive digital agriculture system and the establishment of a vast and insightful database that encompasses the entirety of the agricultural sector. This in-depth review critically examines the future trajectory of digital transforming technologies within Indian agriculture, meticulously analyzing the key components of this integrated system and rigorously evaluating their profound potential impact on the nation's agricultural future.

2. Understanding the Evolving Landscape of Digitization in Indian Agriculture

A significant and growing body of scholarly research has been dedicated to exploring the intricate processes and multifaceted impacts of integrating digitization within the agricultural sector. The comprehensive and insightful report, "State of Indian Agriculture (2015-16)," provides a detailed and nuanced overview of the sector's overall performance, inherent challenges, and potential future directions, meticulously highlighting critical aspects such as evolving growth patterns across different regions, significant regional variations in agricultural development and productivity, the crucial role of capital formation within the agricultural domain, the production performance of diverse crops and livestock, advancements and challenges within the horticulture sector, strategic approaches to land use optimization and diversification, the critical importance of irrigation management and water resource efficiency, the fundamental role of soil health in sustainable agriculture, the imperative of climate change adaptation and mitigation strategies, and the implementation of more effective and data-driven agricultural input management practices.

NITI Aayog's significant 2015 publication strategically focuses on identifying and promoting effective strategies for substantially enhancing overall agricultural productivity and ensuring consistently remunerative returns for Indian farmers, offering valuable insights into addressing the key challenges that currently hinder robust agricultural growth and limit the income potential of farm households. The International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) compellingly emphasizes the transformative potential of digital agriculture as a crucial pathway to achieving widespread and sustainable prosperity within the agricultural community, with the overarching and ambitious aims of making agriculture a consistently

profitable and attractive enterprise, significantly improving the overall livelihoods and resilience of farmers, and effectively contributing to the reduction of poverty levels within rural populations. The regularly published "Agricultural Situation in India (2017)" offers timely and relevant updates on current farm sector news, comprehensive general surveys of prevailing agricultural trends, insightful articles presenting findings from Agro-economic research, detailed commodity reviews analyzing market dynamics, and analyses of significant trends shaping the agricultural landscape. Soma Dhar's significant 2014 study provides a detailed and nuanced analysis of the socio-economic and demographic status of the state of Assam, meticulously highlighting various key facts and figures pertaining to the state's agricultural sector and systematically comparing these with relevant facts and figures representing all-India averages, providing valuable insights into regional disparities and opportunities. Sharma's pertinent 2007 research endeavours to thoroughly understand the complex socio-economic implications of corporate-led initiatives within the agricultural sector, with a primary focus on the prevalent practice of contract farming in the state of Punjab, a region possessing comparatively more extensive experience in the implementation and impact of contract farming when juxtaposed with other states across India.

These foundational studies provide invaluable contextual understanding regarding the current state of Indian agriculture, the initial considerations for integrating digital technologies, and the early observed impacts of these interventions. The subsequent sections of this review will delve deeper into the specific transformative potential of key digital technologies within this evolving integrated framework, exploring their mechanisms, applications, and potential impact on the future of Indian agriculture.

3. Key Technologies Driving the Future of Digital Agriculture in India

The future of digital transformation in Indian agriculture will be significantly propelled by the synergistic and strategic application of several advanced and rapidly evolving technologies, creating a more efficient, sustainable, and resilient agricultural ecosystem:

3.1. Advanced Sensor Systems: The very bedrock of an efficient and responsive integrated agricultural system lies in its fundamental ability to accurately and reliably collect granular, real-time data across the entirety of the agricultural value chain. Future advancements in sensor technology will be characterized by the development of even more robust, highly cost-effective, and remarkably versatile sensor devices. These next-generation sensors will possess the capability to monitor an even wider and more diverse array of critical agricultural parameters, spanning from the intricate nuances of soil health and precise plant physiological responses to the dynamic conditions within storage facilities and the complex logistical flows of the supply chain. This technological evolution will encompass sophisticated hyperspectral imaging sensors enabling detailed and non-destructive plant health analysis by capturing data across a wide range of the electromagnetic spectrum, revealing subtle stress indicators and nutrient

deficiencies; highly specific electrochemical and optical nutrient-detecting soil sensors providing real-time in-situ information on key nutrient levels (NPK, micronutrients) and crucial soil properties like pH and electrical conductivity; advanced environmental sensors capable of accurately predicting localized microclimate changes, including temperature inversions, humidity fluctuations, and solar radiation intensity; and intelligent sensors specifically designed for continuous monitoring of the quality and safety of agricultural produce throughout its storage and transportation journey, tracking parameters like temperature, humidity, ethylene levels, and potential spoilage indicators. The seamless integration of energy-efficient and high-

bandwidth wireless sensor networks (WSNs), utilizing protocols like LoRaWAN, NB-IoT, and Zigbee, will facilitate denser and more comprehensive data collection across expansive farm areas and intricate supply chain networks (Abbasi *et al.*, 2024) ^[1]. Moreover, the development and deployment of self-calibrating and exceptionally low-maintenance sensor systems, potentially incorporating advanced materials and energy harvesting techniques, will significantly reduce operational overhead and ensure the consistent acquisition of highly accurate data over extended periods, making them more accessible to smallholder farmers.

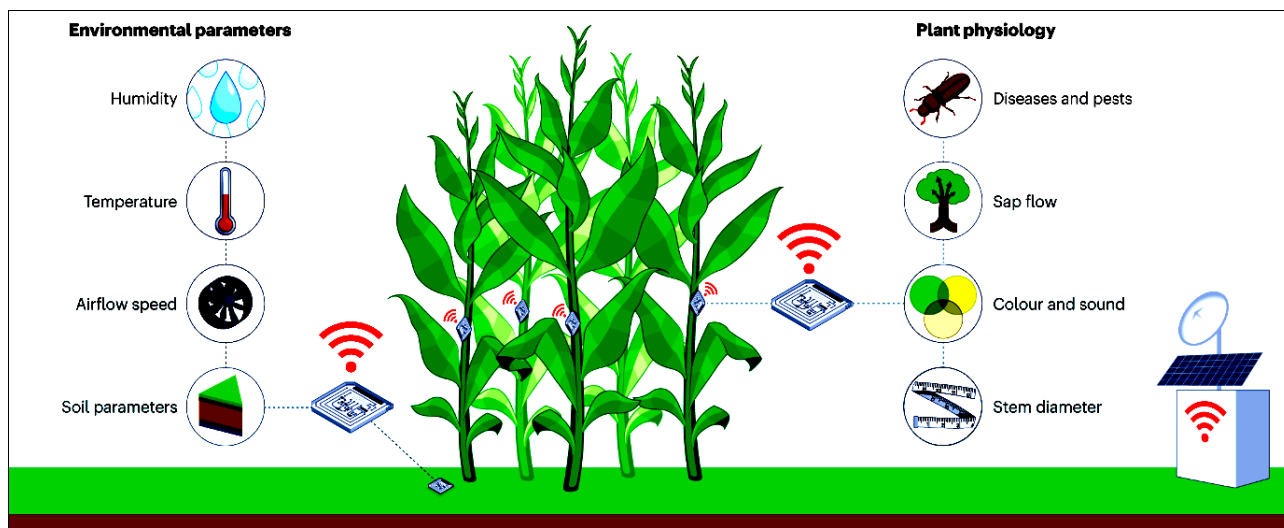


Fig 1: Examples of Advanced Sensors in Agriculture

[Image grid showing: a) A high-precision electrochemical soil nutrient sensor probe inserted into the ground, providing real-time data on NPK levels and pH wirelessly to a farmer's device; b) A drone equipped with a lightweight, high-resolution multispectral camera capturing detailed vegetative indices and stress patterns across a large field, generating actionable insights on plant health; c) Compact, low-power wireless temperature and humidity sensors strategically placed within a controlled atmosphere storage facility, transmitting critical data on preservation conditions to a cloud platform for remote monitoring; d) Active RFID tags or BLE beacons attached to individual livestock, enabling precise location tracking, activity monitoring (e.g., grazing patterns, rumination), and physiological data collection via integrated biosensors (e.g., body temperature).

3.2. Enhanced Internet of Things (IoT) Infrastructure:

Uninterrupted and secure connectivity, coupled with the efficient exchange of vast amounts of data, forms the very nervous system of a truly integrated agricultural system. Future developments in this critical area will prioritize the strategic expansion and significant enhancement of IoT infrastructure specifically tailored for the unique challenges and dispersed nature of rural India. This will necessitate the deployment of more pervasive and reliable network

coverage, encompassing advanced technologies such as robust 5G networks and resilient satellite-based communication systems (e.g., Starlink, OneWeb) to ensure ubiquitous connectivity even in the most remote agricultural regions. Furthermore, reducing network latency and significantly increasing bandwidth will be crucial to effectively support the exponentially growing volume of data generated by the multitude of interconnected agricultural devices and intelligent systems operating across all stages of production, distribution, and consumption. The rigorous development and implementation of highly secure and seamlessly interoperable IoT platforms, adhering to open standards and robust cybersecurity protocols, will be paramount for the effective integration of diverse devices from various manufacturers while stringently ensuring the privacy and security of sensitive agricultural data (Abiri *et al.*, 2024) ^[3]. The strategic deployment of edge computing capabilities, enabling data processing and preliminary analysis closer to the data source (e.g., on farm gateways or within processing facilities), will gain increasing importance for facilitating rapid, real-time decision-making in geographically remote agricultural locations and for time-critical applications operating within the integrated system, reducing reliance on constant cloud connectivity and improving responsiveness.

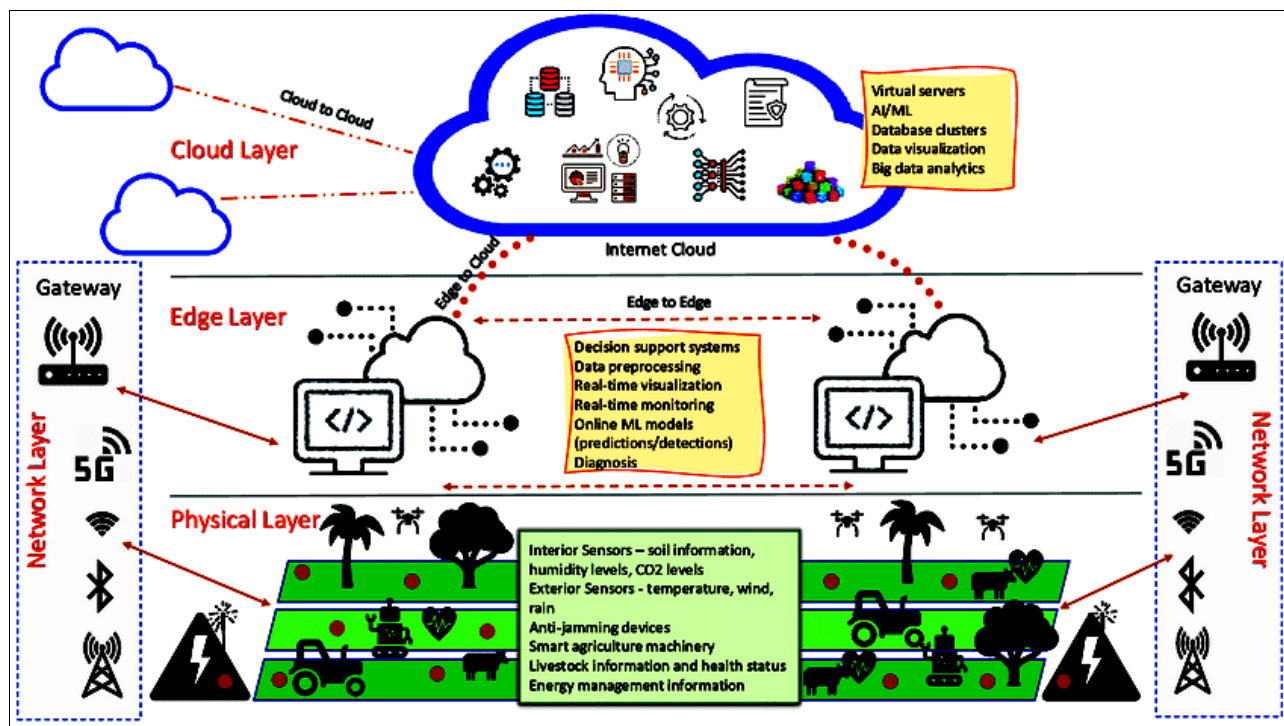


Fig 2: Future-Ready IoT Architecture for Smart Agriculture in India

[Diagram illustrating a sophisticated, multi-layered IoT architecture optimized for Indian agriculture:

- **Layer 1 (Intelligent End Devices):** A diverse array of advanced sensors (environmental, soil, plant, animal), smart actuators (precision irrigation valves, variable rate applicators), autonomous robots, drone-based data acquisition systems, smart packaging, and logistics tracking devices.
- **Layer 2 (Robust Connectivity & Edge Computing):** Secure and high-bandwidth communication networks (5G, LoRaWAN, NB-IoT, satellite), strategically placed edge computing nodes for localized data processing, filtering, and real-time control, and secure data aggregation gateways.
- **Layer 3 (Scalable Cloud Platform):** A secure and scalable cloud infrastructure (public, private, or hybrid) for centralized data storage, advanced analytics (AI/ML), seamless integration with other agricultural information systems and services (e.g., weather APIs, market platforms), and robust data governance frameworks.
- **Layer 4 (Intelligent Applications & User-Centric Interfaces):** AI-powered applications providing predictive insights, personalized recommendations, and intuitive control interfaces (mobile apps, web dashboards) accessible in local languages for farmers, processors, distributors, retailers, and consumers, with role-based access control and data visualization tools.]

3.3. Artificial Intelligence (AI) and Machine Learning (ML) with Deeper Insights: Artificial Intelligence and Machine Learning will remain absolutely central to the intelligent analysis of the vast and complex datasets

generated within the integrated agricultural system, unlocking significantly deeper and more immediately actionable insights than ever before. Future advancements in this critical domain will involve the continuous refinement and deployment of increasingly sophisticated AI algorithms. These advanced algorithms will be capable of generating substantially improved and highly accurate predictive models for critical agricultural outcomes such as precise yield forecasting under diverse conditions (considering weather patterns, soil variability, and historical data), early and accurate detection of disease and pest outbreaks across various crop stages and storage environments (leveraging image recognition, spectral analysis, and environmental data), and highly optimized recommendations for resource allocation (water, fertilizers, pesticides) meticulously tailored to specific crop varieties, localized soil conditions, and even dynamic logistical constraints within the distribution network. Furthermore, AI-powered intelligent systems will play an increasingly vital role in enhancing automation across the value chain, including sophisticated quality control measures during processing stages (using AI-driven vision systems for defect detection and grading) and highly accurate demand forecasting to optimize production planning, minimize waste in the supply chain, and inform consumption patterns. The synergistic integration of AI with advanced computer vision techniques will further enhance capabilities in critical areas such as automated and objective grading of agricultural produce based on a wider range of quality parameters (size, shape, color, texture), and continuous monitoring of stringent food safety standards throughout the entire supply chain (detecting contamination, verifying handling procedures).

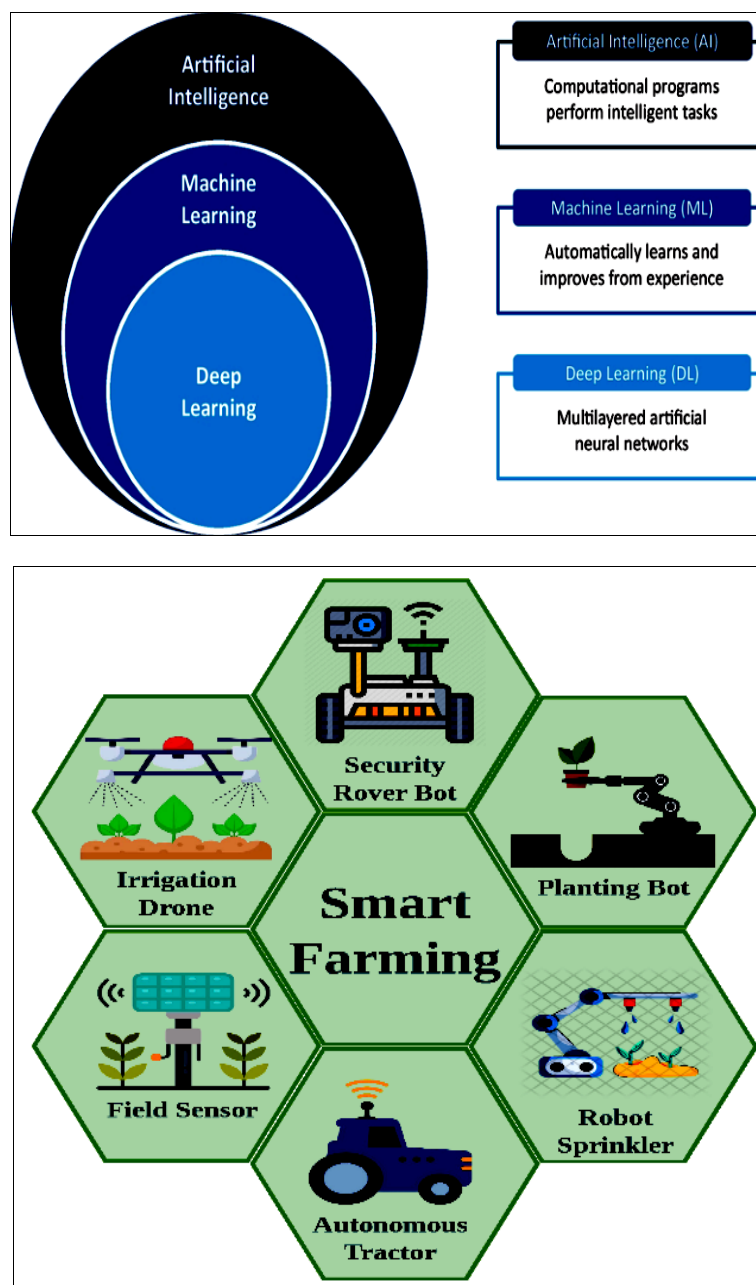


Fig 3: Advanced AI and ML Applications Transforming Indian Agriculture

[Image montage showcasing: a) A farmer using a smartphone app powered by AI to diagnose a specific plant disease by simply taking a picture of the affected leaf, receiving instant treatment recommendations in their local language; b) A dynamic dashboard displaying ML-predicted optimal irrigation schedules for different zones of a farm, visualized on a map and automatically controlling smart irrigation valves based on real-time data; c) A detailed geospatial yield forecasting map generated by AI algorithms analyzing high-resolution satellite imagery, historical yield data, and hyperlocal weather forecasts, providing precise yield estimates at the individual field level and informing market strategies; d) An AI-driven system analyzing video streams from livestock farms to automatically detect early signs of illness or abnormal behavior in animals (e.g., changes in gait, reduced activity), triggering alerts for proactive veterinary intervention.

3.4. Autonomous Robotics and Intelligent Automation:

The strategic deployment of autonomous robotics and intelligent automation technologies will fundamentally transform the efficiency, precision, and reduce the reliance on manual labor across the entire integrated agricultural system. Future developments in this rapidly advancing field will witness the emergence of even more versatile, highly adaptable, and remarkably intelligent agricultural robots. These advanced robotic systems will be capable of performing a significantly wider range of complex tasks with exceptional precision and complete autonomy, spanning from intricate field operations such as ultra-precision planting at optimal depths and spacing, targeted autonomous weeding using AI-powered computer vision to distinguish weeds from crops, and sophisticated harvesting of diverse and delicate crops using advanced manipulation and sensing capabilities, to critical tasks in processing facilities such as automated sorting, grading, and packaging,

and even potentially in logistics for autonomous transportation within farms and processing centers. Unmanned Aerial Vehicles (UAVs) will evolve with significantly enhanced flight endurance, extended battery life (potentially through solar power or hybrid systems), and integration of even more sophisticated and multi-functional sensor payloads, including LiDAR for 3D mapping and biomass estimation, thermal cameras for plant stress detection, and specialized spray nozzles for ultra-precise application of inputs. This will enable more detailed and frequent aerial monitoring of crop health and land conditions, as well as highly efficient and targeted delivery

of agricultural inputs (fertilizers, pesticides) and comprehensive surveillance of storage facilities and transportation networks for security and condition monitoring. The deep and seamless integration of Artificial Intelligence with these advanced autonomous systems will culminate in the creation of truly intelligent agricultural automation, capable of dynamically optimizing processes, autonomously adapting to changing environmental conditions and task requirements, and even learning from past experiences to continuously improve performance across the entire integrated agricultural system (Fountas *et al.*, 2024) ^[9].

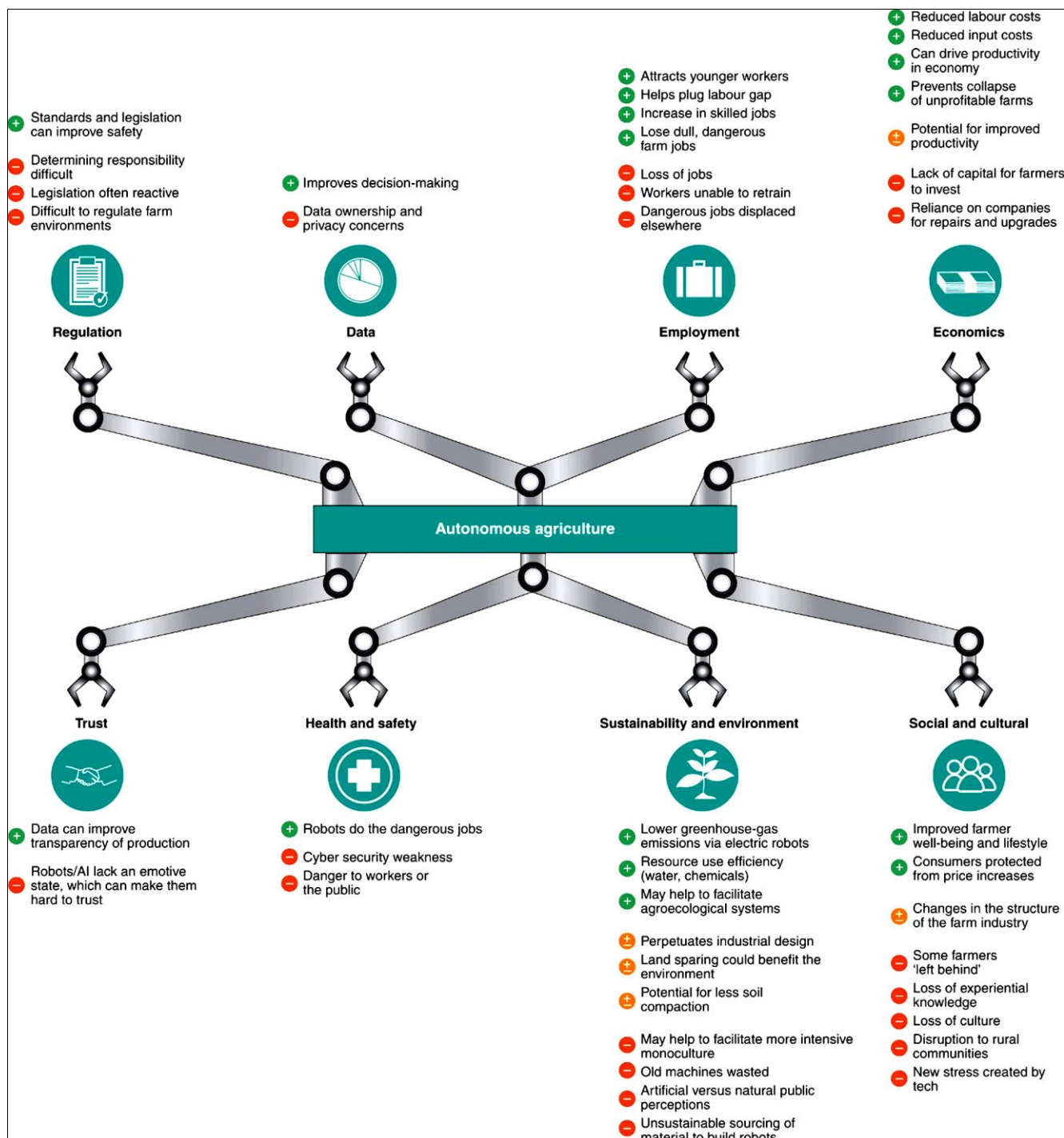


Fig 5: The Future of Agricultural Robotics and UAVs in India

[Image showcasing: a) A swarm of small, agile, solar-powered robots autonomously planting seeds with centimeter-level accuracy in a large field, guided by GPS and real-time soil data; b) A heavy-duty autonomous ground vehicle equipped with advanced sensors and multiple robotic arms harvesting a delicate fruit crop (e.g., mangoes) with minimal bruising, using AI-powered vision to identify ripe fruits; c) A fleet of interconnected UAVs collaboratively monitoring crop health over a vast agricultural landscape, sharing real-time multispectral and thermal imagery and autonomously identifying areas requiring immediate intervention (e.g., pest infestation); d) An intelligent robotic system operating within a food processing facility, autonomously sorting and grading fruits and vegetables based on pre-defined quality parameters (size, shape, color, blemishes) using advanced 3D vision systems and gentle handling mechanisms.]

3.5. Big Data Analytics and Cloud-Based Platforms:

Effective management, secure storage, and intelligent analysis of the exponentially growing volumes of heterogeneous data generated across the integrated agricultural system are absolutely critical for unlocking its full potential and driving data-driven decision-making at all levels. Future advancements in the field of big data analytics will focus on the development of even more user-friendly, highly intuitive, and powerfully insightful platforms. These advanced platforms will possess the capability to seamlessly integrate data originating from a multitude of diverse sources spanning production (sensor data, farm management systems), distribution (logistics data, environmental conditions during transport), and consumption (market prices, consumer feedback, sales data), providing all stakeholders with immediately actionable insights through sophisticated data visualization tools, comprehensive and customizable reporting functionalities, and robust support for collaborative decision-making processes across the entire value chain. Secure and highly scalable cloud-based platforms (public, private, or hybrid) will continue to provide the essential infrastructure required for the efficient and cost-effective storage, high-performance processing, and seamless deployment of advanced AI and ML models, ensuring data accessibility and security. The development of industry-specific cloud solutions tailored to the unique needs of the Indian integrated agricultural system will be crucial (Kareska, 2024) ^[6].

3.6. Blockchain Technology for Enhanced Traceability and Transparency:

Blockchain technology offers a significant opportunity to enhance transparency and build trust within the integrated agricultural system. By providing a secure and immutable ledger for tracking agricultural products from farm to consumer, blockchain can improve food safety, reduce fraud, enhance traceability, and empower farmers with greater control over pricing and market access. Its application can extend to verifying organic certifications, tracking inputs, and facilitating direct farmer-to-consumer transactions, thereby streamlining the distribution and consumption aspects of the integrated system.

4. Architecture of Future Integrated Smart Agricultural Systems in India

The architecture of future integrated smart agricultural systems in India will likely evolve towards more interconnected, distributed, and intelligent frameworks that span the entire agricultural value chain:

- **Hyper-Connected Ecosystems:** A dense network of interconnected sensors, actuators, robots, processing units, logistics trackers, and even consumer feedback systems, leveraging advancements in IoT and communication technologies.
- **Edge Intelligence:** Increased processing capabilities at the edge of the network (on devices, local hubs, processing facilities) to enable faster real-time decision-making and reduce reliance on constant cloud connectivity across all stages.
- **AI-Driven Orchestration:** Centralized AI platforms that orchestrate the operation of various autonomous systems and optimize processes across production, distribution, and consumption, providing proactive recommendations based on integrated data analysis.
- **Modular and Scalable Platforms:** Flexible and scalable software and hardware platforms that can be easily adapted to the diverse needs and scales of operations within the Indian agricultural landscape, from smallholder farms to large-scale processing and distribution networks.
- **Enhanced User Interfaces:** More intuitive and user-friendly interfaces (mobile apps, web portals) that provide all stakeholders, from farmers to consumers, with personalized insights, actionable recommendations, and control over relevant aspects of the integrated system in their local languages.
- **Integration with National Agricultural Infrastructure:** Seamless integration with national agricultural databases, weather forecasting services, market information platforms, and logistics networks to provide a holistic and efficient integrated system.
- **Secure and Private Data Management:** Robust security measures and data privacy protocols to protect sensitive agricultural data across all stages of the integrated system.

(Adapt Figure 2 from the previous response to reflect these future trends, emphasizing greater integration across the value chain, edge intelligence, and AI-driven orchestration for the entire integrated system.)

5. Conclusion: Realizing the Transformative Potential of Integrated Digital Agriculture in India

The digital transformation of Indian agriculture towards a fully integrated system holds immense promise for enhancing efficiency, ensuring food security, promoting sustainability, improving farmer livelihoods, and meeting consumer demands. The strategic and synergistic adoption of advanced sensors, robust IoT infrastructure, sophisticated AI and ML algorithms, autonomous robotics, big data analytics, cloud computing, and blockchain technology will be crucial in realizing this vision. However, overcoming challenges related to digital literacy, infrastructure

limitations in rural areas, the affordability of technology for smallholder farmers, and ensuring data privacy and security across the integrated system will be paramount for widespread success. Concerted efforts from government bodies, research institutions, technology providers, agricultural organizations, and the active participation of farmers are essential. By fostering collaboration, investing in research and development, implementing effective policies, building robust infrastructure, and focusing on creating accessible and user-friendly digital solutions tailored to the Indian context, the nation can unlock the transformative potential of integrated digital agriculture and build a more resilient, efficient, and prosperous agricultural future for all stakeholders.

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