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Sustainable Farming for the Future: A Conceptual Framework for Integrating Smart Technologies and Sustainability in Small-Scale Agriculture

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Abstract

Smallholder farmers remain the backbone of the global food system, contributing substantially to food security, rural employment, and economic development. However, they face increasing challenges arising from climate change, resource scarcity, environmental degradation, and socio-economic constraints. Recent advancements in Information and Communication Technologies (ICT), including the Internet of Things (IoT), artificial intelligence (AI), unmanned aerial vehicles (UAVs), decision support systems (DSS), and blockchain, have introduced new opportunities for transforming traditional agriculture into smart and sustainable farming systems. This literature review integrates two major perspectives—smart farming and sustainable agriculture—into a unified conceptual framework. Drawing upon recent scholarly literature, the review examines how high-tech tools enhance productivity, environmental stewardship, social empowerment, and governance transparency, particularly within small-scale farming systems. Furthermore, the paper highlights key barriers to technology adoption and outlines future research directions. The findings demonstrate that the integration of digital technologies into smallholder agriculture holds significant potential to enhance resilience, sustainability, and long-term food security.

1. Introduction

Smallholder farmers account for more than 80% of farms worldwide and contribute substantially to global food production, especially in developing economies (Satpathy, 2022). Despite their importance, small-scale farmers operate under increasing constraints, including climate variability, rising input costs, water scarcity, soil degradation, and limited access to markets and information (Touch et al., 2024). These challenges threaten not only rural livelihoods but also long-term food security and environmental sustainability (Touch et al., 2024).

In response, digital and high-tech agricultural innovations often called smart farming, precision agriculture, or digital agriculture—have emerged as transformative solutions. Technologies such as IoT-based sensors, UAVs (drones), machine learning, big data analytics, and blockchain enable data-driven decision-making, precise resource management, and transparent supply chain governance (Jain et al., 2025). At the same time, the global sustainability agenda, framed under Environmental, Social, and Governance (ESG) principles, emphasizes the need for environmentally responsible, socially inclusive, and ethically governed agricultural systems (Gamage et al., 2024).

This literature review integrates these two perspectives by proposing a comprehensive framework for smart and sustainable farming. Specifically, it explores how digital technologies contribute to environmental conservation, social empowerment, and governance improvement in small-scale agriculture. By synthesizing existing empirical and conceptual studies, this paper aims to establish a holistic understanding of how smart farming technologies can support sustainable development goals.

2. Conceptual Foundations: Smart Farming and Sustainability

2.1 Smart Farming and Precision Agriculture

Smart farming refers to the application of advanced digital technologies to enhance agricultural productivity, efficiency, and sustainability (Checchinato et al., 2022). Precision agriculture, a closely related concept, involves the site-specific management of crops using real-time data, remote sensing, and automation (Abdalla & El-Ramady, 2022). The fundamental principle is to replace generalised farming practices with targeted interventions based on accurate field-level data (Mgendi, 2024).

Core technologies enabling smart farming include:

- Internet of Things (IoT): Networked sensors monitoring soil moisture, temperature, humidity, and nutrient levels. (Rajak et al., 2023)
- Unmanned Aerial Vehicles (UAVs): High-resolution aerial imagery for crop health assessment, pest detection, and yield estimation. (Villa-Henriksen et al., 2020)
- Artificial Intelligence (AI) and Machine Learning (ML): Advanced analytics for predictive modelling, disease detection, and decision optimisation. (Mansoor et al., 2025)
- Decision Support Systems (DSS): Integrated platforms providing actionable insights for farm management. (Kushwaha et al., 2024)

Studies consistently report that smart farming technologies improve productivity, reduce resource waste, and enhance farm profitability (Mandapuram et al., 2019; Abiri, et al., 2023). These tools—from the disease-spotting drones in Turkey to the water-saving IoT systems in Vietnam—are not just technological novelties; they deliver tangible results that benefit both the farmer's bottom line and the planet's health (Onike, 2025). By making agriculture more precise and efficient, these smart technologies create a system that is both more productive and profoundly more sustainable.

Table 1 *Benefits of smart farming for farmers and the environment*

Benefits for the Farmer	Benefits for the Environment
Enhanced Decision-Making with real-time data & insights	Optimised Resource Management (e.g., soil, fertiliser)
Increased Crop Yields and overall productivity	Significant Water Savings through precision irrigation
Improved Product Quality and market value	Reduced Reliance on Chemicals like pesticides & fertilizers

2.2 Sustainability and the ESG Framework

Sustainable agriculture emphasises the long-term viability of farming systems by balancing economic productivity, environmental protection, and social equity (Kareska, 2025). The ESG framework—Environmental, Social, and Governance—offers a structured approach to evaluating sustainability outcomes across multiple dimensions (Almeida et al., 2024).

- Environmental (E): Conservation of natural resources, climate resilience, reduced pollution, and biodiversity protection. Smart technologies promote environmental stewardship by optimising resource management and reducing the ecological footprint of farming.
    - ➢ Water Conservation: IoT-based sensors monitor soil moisture and humidity in real-time. In Vietnam, for instance, IoT-supported irrigation systems reduced water consumption by up to 30% while simultaneously increasing rice yields (Mallareddy et al., 2023).
    - ➢ Reduced Chemical Inputs: Unmanned Aerial Vehicles (UAVs) and AI-driven imagery allow for the early detection of pests and diseases. This enables targeted interventions, which minimise the overall use of pesticides and fertilisers, thereby reducing soil and water contamination. (Zhu, et al., 2024).
    - ➢ Climate Resilience: AI-powered predictive modelling and climate risk forecasting help smallholders adapt to weather variability, enhancing the farm's ability to withstand climate-related shocks (Roy, et al., 2025).

- Social (S): The social dimension of smart farming focuses on farmer empowerment, food security, and rural livelihood stability.
    - ➢ Economic Stability: By improving crop yields and product quality through precise resource application, smart technologies help stabilise and increase farmer incomes. Tools like fertiliser optimisation systems have been shown to improve adoption attitudes by aligning with a farmer's financial capacity (Ivanovich, et al., 2024).
    - ➢ Food Security: Early warning systems powered by UAVs and AI protect smallholders against production risks, directly strengthening local and global food security (Istiak, et al., 2023).

- Governance (G): Governance improvements are primarily driven by transparency and accountability within the agricultural supply chain
    - ➢ Market Access: Transparent digital supply chains facilitate smallholders' access to premium markets and fair-trade opportunities by proving compliance with quality and sustainability standards (Bager, et al., 2022)
    - ➢ Data Governance: Digital platforms support better institutional accountability and can streamline complex bureaucratic processes, such as certification documentation, which often act as barriers for small operators (Istiak, et al., 2023)

While these technologies offer significant potential to align smallholder farming with the United Nations Sustainable Development Goals, their success depends on overcoming barriers such as high capital costs, digital literacy gaps, and inadequate rural infrastructure.

Integrating ESG principles into agriculture aligns farming systems with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

3. Technological Enablers of Smart and Sustainable Farming

3.1 IoT and Sensor-Based Systems

IoT-based technologies play a foundational role in smart agriculture by enabling continuous real-time data collection. Sensors installed in soil, irrigation systems, and storage facilities provide actionable insights for optimizing farm operations (Ray, 2017).

Empirical studies demonstrate significant benefits. In Vietnam, IoT-supported Alternate Wetting and Drying (AWD) irrigation systems reduced water consumption by up to 30% while increasing rice yields (Lampayan et al., 2015). Similarly, studies in Italy and China reported enhanced irrigation efficiency and improved crop quality through sensor-guided environmental control systems (Laphatphakkhanut et al., 2021)

3.2 UAVs and Remote Sensing

Drones equipped with multispectral and thermal cameras provide high-resolution imagery for crop health assessment, nutrient stress detection, and disease monitoring (Ballabh et al., 2022). UAV-based monitoring significantly improves early detection of pests and diseases, enabling targeted interventions and minimising chemical usage (Zhu et al., 2024).

In Turkey, deep learning models applied to UAV images achieved high accuracy in plant disease detection, enhancing operational efficiency and reducing crop losses (Ahmed et al., 2024). Similar applications in Malaysia and South Africa highlight drones' effectiveness in plantation management and land mapping (Abdullah et al., 2020).

3.3 Artificial Intelligence and Machine Learning

AI-driven analytics enable predictive modelling for yield estimation, climate risk forecasting, and pest outbreak prediction. Convolutional Neural Networks (CNNs) have demonstrated superior accuracy in rice yield prediction compared to traditional statistical methods (Rane et al., 2024). AI-based diagnostic tools deployed in Uganda significantly improved farmers' ability to detect crop diseases, reducing reliance on chemical pesticides (Rane et al., 2024).

3.4 Blockchain and Digital Platforms

Blockchain technology enhances traceability, transparency, and trust across agricultural supply chains. By providing immutable transaction records, blockchain enables food provenance tracking, certification verification, and ethical sourcing (Hilten et al., 2020). Digital platforms further support governance by facilitating data sharing, market access, and financial inclusion (Lai et al., 2025).

4. Smart Farming through the ESG Lens

Viewing smart farming through the ESG lens (Environmental, Social, and Governance) provides a structured framework for transforming smallholder agriculture from traditional practices into a sustainable, data-driven system. This integration aligns technological innovation with global objectives like the United Nations Sustainable Development Goals, specifically SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

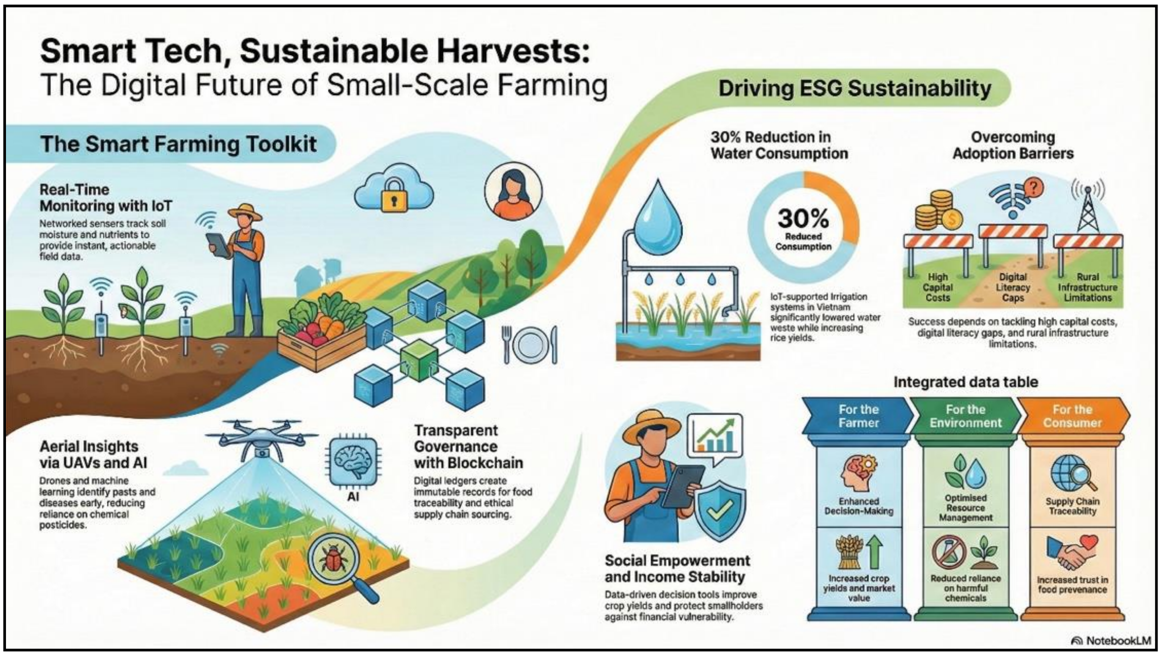

Fig. 1 *Integration of technological innovation on smart farming through the ESG lens (Environmental, social, and governance)*

4.1 Environmental Sustainability (E)

Smart technologies contribute to environmental conservation through precision resource management, reduced chemical inputs, and enhanced climate resilience. IoT-based irrigation systems significantly reduce water waste, while UAV monitoring enables early pest detection, minimising pesticide use (Et-taibi et al., 2024). AI-powered climate prediction tools further assist farmers in adapting to weather variability.

4.2 Social Empowerment (S)

Digital agriculture empowers farmers by improving access to information, enhancing decision-making, and increasing income stability. Fertiliser optimisation tools tailored to farmers' financial capacity have been shown to increase yields and improve adoption attitudes (Baviskar, 2024). Early warning systems reduce vulnerability to crop failure, thereby strengthening rural livelihoods and food security.

4.3 Governance and Transparency (G)

Blockchain-based traceability systems enhance transparency and accountability, improving consumer trust and enabling fair trade practices. Studies indicate that transparent digital supply chains improve market access for smallholders and strengthen compliance with quality standards (Ibrahim et al., 2024).

Table 2 *Technology supports ESG in farming*

ESG Pillar	Technology Example	Positive Impact for Smallholders
Environmental	IoT for Precision Irrigation	Reduces water waste and enhances crop yields. (García, et al., 2020)
Social	Decision Support Tools (e.g., Fertilizer Optimization)	Empowers farmers with data, improving crop yields and income (Desta, et al., 2023).
Governance	Blockchain	Increases transparency and trust in the food supply chain (Cozzio, et al., 2023).

5. Barriers to Technology Adoption among Smallholders

Despite promising benefits, technology adoption remains constrained by several factors:

1. High Capital Costs: Initial investment in sensors, drones, and AI systems remains prohibitive for many smallholders (Klerkx et al., 2019; Salemink, et al., 2017).
2. Digital Literacy Gaps: Limited technological knowledge and training reduce farmers' capacity to utilise digital tools effectively (Trendov et al., 2019; Khatri, et al., 2024).
3. Infrastructure Limitations: Poor internet connectivity and unreliable electricity supply hinder system deployment in rural areas. (Salemink, et al., 2017).
4. Data Governance and Privacy Concerns: Farmers express apprehension regarding data ownership, misuse, and surveillance (Silveira et al., 2025)
5. Complex Processes: Sometimes the biggest hurdle is bureaucracy. For example, in a study of the Malaysian Good Agricultural Practices (myGAP) certification, farmers reported that the lengthy and complex process, with its extensive documentation requirements, was a major obstacle for small operators who lack dedicated administrative staff. (Mohd Arifin et al., 2024)

Addressing these barriers requires targeted policy interventions, inclusive innovation ecosystems, and capacity-building initiatives.

6. Discussions

The synthesis of existing literature demonstrates that the integration of smart farming technologies into small-scale agriculture has profound implications for productivity, sustainability, and resilience. The findings reveal that digital tools such as the Internet of Things (IoT), artificial intelligence (AI), unmanned aerial vehicles (UAVs), decision support systems (DSS), and blockchain are not merely incremental innovations but represent a structural transformation in agricultural systems.

From an environmental perspective, smart farming technologies significantly enhance resource-use efficiency. Empirical evidence indicates that sensor-based irrigation systems and precision water management techniques can substantially reduce water consumption while maintaining or increasing crop yields (Lampayan et al., 2015). Similarly, UAV-enabled crop monitoring and AI-driven pest detection systems enable early intervention, thereby minimizing chemical usage and reducing environmental contamination (Mohanty et al., 2016; Ferentinos, 2018). These outcomes align closely with sustainability goals, particularly those related to climate resilience, water conservation, and ecological preservation. The results suggest that smart farming can serve as a key enabler of environmentally sustainable agricultural practices, particularly in regions vulnerable to climate change.

From a social dimension, digital agriculture enhances farmer empowerment, income stability, and food security. Decision support tools tailored to local agronomic and socio-economic conditions provide actionable insights that improve farm-level decision-making, resulting in increased productivity and reduced production risks (Raihan et al., 2022). Early-warning systems supported by AI and UAV technologies further protect smallholders against crop failures, which are a major source of financial vulnerability. These findings highlight the role of technology in strengthening rural livelihoods and promoting inclusive agricultural development. However, disparities in digital literacy and access to infrastructure remain major challenges, potentially exacerbating existing inequalities if not addressed through targeted training and policy interventions.

In terms of governance, blockchain-based traceability and digital platforms introduce new standards of transparency, accountability, and trust in agricultural value chains. The literature emphasises that transparent supply chains improve consumer confidence, enhance regulatory compliance, and facilitate access to premium markets for smallholders (Tian, 2017; Kamilaris et al., 2019). Moreover, digital data governance frameworks can support fair trade practices and strengthen institutional accountability. Nevertheless, concerns regarding data privacy, ownership, and ethical data use remain insufficiently addressed, particularly in developing economies where regulatory frameworks are still evolving. This highlights the urgent need for comprehensive data governance policies to ensure farmer protection and equitable benefit sharing.

Despite these promising outcomes, adoption barriers remain substantial. High investment costs, limited access to financing, inadequate digital infrastructure, and low technological literacy continue to hinder widespread technology uptake among smallholder farmers (Klerkx et al., 2019; Trendov et al., 2019). Furthermore, sociocultural factors, including resistance to change and limited trust in digital systems, also influence adoption behaviour. These challenges suggest that technology diffusion must be accompanied by supportive policies, capacity-building programs, and participatory innovation models that actively involve farmers in system design and implementation.

Overall, the discussion underscores that the successful integration of smart farming technologies requires a holistic approach that simultaneously addresses technological, socio-economic, institutional, and governance dimensions. Future research should therefore prioritize interdisciplinary frameworks that combine agronomy, information systems, development studies, and policy analysis to better understand the complex dynamics shaping digital agriculture adoption and impact.

7. Conclusions

This literature review has systematically examined the role of smart farming technologies in advancing sustainable small-scale agriculture through an integrated Environmental, Social, and Governance (ESG) framework. The findings provide compelling evidence that digital innovations including IoT, AI, UAVs, DSS, and blockchain—offer transformative potential for enhancing agricultural productivity, environmental sustainability, farmer empowerment, and governance transparency.

From an environmental standpoint, smart farming enables precision resource management, reduces water and chemical usage, and strengthens climate resilience. Socially, these technologies improve farm-level decision-making, increase productivity, stabilize incomes, and enhance food security. In terms of governance, blockchain and digital platforms foster transparency, traceability, and accountability across agricultural supply chains, strengthening trust among farmers, consumers, and regulatory institutions.

However, the realization of these benefits is contingent upon addressing persistent adoption barriers, particularly high implementation costs, limited digital literacy, inadequate rural infrastructure, and weak data governance frameworks. Without targeted interventions, there is a risk that digital agriculture may widen existing socio-economic disparities rather than promote inclusive development. Therefore, policy support, public–private partnerships, financial incentives, and farmer centered capacity building programs are essential to ensure equitable technology diffusion.

In conclusion, the convergence of smart farming and sustainability principles represents a strategic pathway toward resilient, inclusive, and environmentally responsible agricultural systems. By aligning technological innovation with ESG objectives, stakeholders can accelerate progress toward global food security and sustainable development goals. Future research should focus on longitudinal impact assessments, localized technology adaptation, and policy-driven innovation ecosystems to fully harness the transformative power of digital agriculture for smallholder farmers.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

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