



Application of the internet of things in smart agriculture: A review of approaches, evidence, and implementation challenges

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Abstract

The Internet of Things (IoT) has become a foundational technology for modern precision and smart agriculture, connecting sensors, microcontrollers, wireless networks, and cloud or edge computing platforms to enable real-time monitoring and automated decision-making on farms. This narrative literature review synthesizes findings from systematic reviews, bibliometric analyses, and meta-analyses published largely between 2023 and 2026 to examine the major approaches through which IoT is applied in agriculture, the accumulated evidence on its effectiveness, and the barriers that continue to constrain widespread adoption. The review covers four core application areas: IoT-based smart irrigation and water management, environmental and soil sensing, crop and pest monitoring supported by AI-driven analytics, and farm automation and edge/cloud integration. Across the reviewed literature, IoT-enabled irrigation systems are reported to reduce water use by roughly 9 to 50 percent relative to conventional irrigation while maintaining or improving yields, and a large-scale meta-analysis of 85 global studies found that precision agriculture technology adoption increases average return on investment by 22.3 percent and net profit by 18.5 percent, alongside measurable reductions in nitrogen loss, pesticide use, and greenhouse gas emissions. At the same time, the literature consistently identifies high upfront infrastructure costs, unreliable rural connectivity and electricity, limited interoperability between platforms, cybersecurity and data-privacy weaknesses, and a persistent digital divide disadvantaging smallholder farmers as the primary barriers to scaled adoption. The review concludes that realizing IoT's agricultural benefits at scale depends less on further sensor innovation than on addressing these structural, economic, and infrastructural barriers, and it outlines implications for practice, policy, and future research.

Keywords: Internet of Things, smart agriculture, precision farming, smart irrigation, sensor networks, sustainable agriculture

Introduction

Global agriculture faces mounting pressure to produce more food with fewer resources, as population growth, climate variability, and freshwater scarcity converge on a sector that already accounts for roughly seventy percent of global freshwater withdrawals. The Internet of Things (IoT), a network of interconnected sensors, actuators, and communication devices capable of collecting and exchanging data with minimal human intervention, has emerged as one of the central technologies through which the agricultural sector is attempting to meet these pressures. By enabling real-time monitoring of soil, crop, and environmental conditions and by supporting automated or semi-automated responses such as irrigation scheduling, IoT underpins much of what is now described as precision or smart agriculture.

Market analyses cited across recent reviews estimate that the global agricultural IoT market is on a steep growth trajectory, with projections ranging from roughly eleven billion dollars in the early 2020s toward figures several times that size by the mid-2030s, reflecting declining sensor costs, improving wireless communication reliability, and the increasing accessibility of cloud computing platforms for agricultural applications. This growth has been accompanied by a rapid expansion of academic research: systematic reviews of the field describe publication counts on IoT-based smart irrigation alone rising more than fivefold between 2018 and 2024, with a particularly sharp increase in studies incorporating artificial intelligence alongside IoT sensing.

Despite this growth in both deployment and research volume, adoption of IoT in agriculture remains highly uneven across regions and farm sizes, and the empirical evidence on its practical benefits, while generally positive, varies considerably by technology type, crop, and context. This paper addresses three questions. First, what are the major approaches through which IoT is currently applied in agricultural teaching—more precisely, agricultural practice and management? Second, what does the accumulated empirical evidence say about the effectiveness of these approaches in terms of resource use, yield, and economic return? Third, what barriers most consistently limit broader and more equitable adoption, and what do they imply for practice and policy going forward?

Review Approach

This paper adopts a narrative literature review approach, informed by the structure and findings of published systematic reviews, bibliometric analyses, and meta-analyses rather than constituting a new systematic review in its own right. Sources were identified through targeted searches of academic databases and search engines, including ScienceDirect, MDPI journals (Sensors, Sustainability, Agriculture), Springer Nature, PLOS ONE, and PubMed/PMC, using combinations of terms such as "IoT," "smart agriculture," "precision agriculture," "smart irrigation," "sensor networks," "meta-analysis," and "systematic review." Priority was given to systematic reviews, bibliometric analyses, and meta-analyses published between 2023 and 2026 in peer-reviewed journals,

supplemented by empirical studies frequently cited within that literature.

Because the underlying technology spans multiple domains—irrigation engineering, sensor electronics, wireless communications, and agronomy—search terms were deliberately broad, and retrieved sources were screened for direct relevance to IoT applications in farm-level agricultural practice. Findings were then organized thematically around the major application areas, quantitative effectiveness evidence, and implementation barriers identified across the retrieved literature, consistent with the structure recommended for applied literature reviews in this subject area.

Major Approaches to IoT in Smart Agriculture

Smart Irrigation and Precision Water Management

The most extensively studied application of IoT in agriculture is smart irrigation. These systems typically combine soil moisture, temperature, and humidity sensors with weather data and evapotranspiration models to determine precise irrigation timing and volume, transmitting data via low-power wireless protocols such as LoRaWAN to cloud or edge platforms that trigger automated pump or valve control. A systematic review of IoT-based automated irrigation solutions describes this pipeline as spanning the full chain from data collection through decision-support logic to physical application, with growing attention to interoperability, standardization, and cybersecurity across the automation stack (Nsoh et al., 2024) ^[4].

Reviews of this literature report that LoRaWAN and cloud-based platforms dominate current deployments, appearing in roughly sixty percent of reviewed systems, reflecting their suitability for the low-bandwidth, wide-area, and power-constrained conditions typical of farm environments. Complementary work on low-cost, low-power edge AI and TinyML approaches shows a parallel trend toward pushing predictive irrigation-scheduling models directly onto microcontroller-class devices, enabling on-device decision-making without constant cloud connectivity—an approach particularly relevant for regions with unreliable internet access.

Environmental and Soil Sensing

A second major application area involves continuous environmental and soil sensing to support broader precision-agriculture decision-making beyond irrigation alone. Systematic reviews of smart sensing technologies describe the use of optical, acoustic, electromagnetic, and soil-specific sensors to monitor variables such as soil electrical conductivity, nutrient status, and moisture at multiple root-zone depths, feeding this data into machine learning models—including support vector machines, convolutional neural networks, and random forests—to optimize irrigation, fertilization, and pest-management strategies (Miller et al., 2025) ^[2]. This sensing layer forms the data backbone on which most other smart-agriculture applications, including automated irrigation and predictive analytics, ultimately depend.

Crop and Pest Monitoring with AI-Driven Analytics

IoT sensor networks are also increasingly paired with unmanned aerial vehicles (UAVs) and computer-vision models to support crop health assessment, disease detection, and pest management. Reviews of this combined IoT-AI application area describe systems that use aerial and ground-

based imaging alongside environmental sensor data to detect early signs of crop stress or disease outbreaks, enabling targeted rather than blanket pesticide application. This integration reflects a broader shift identified across the literature: IoT provides the real-time data-collection infrastructure, while AI-driven analytics increasingly provide the interpretive and predictive layer that converts raw sensor readings into actionable farm-management decisions.

Farm Automation and Edge-Cloud Integration

A fourth application area concerns broader farm automation, including land mapping, automated crop prediction, and integrated management platforms that combine multiple IoT data streams into unified dashboards for farmers. A representative example combines land-mapping, crop-prediction, and irrigation-control functions within a single IoT-driven precision-agriculture platform, illustrating a trend toward consolidated systems rather than single-purpose sensor deployments (Saha et al., 2025) ^[5]. Alongside this consolidation, reviews note a parallel architectural shift from purely cloud-centric processing toward hybrid edge-cloud designs, in which time-sensitive decisions are handled locally on low-power edge devices while cloud platforms retain longer-term data storage and cross-farm analytics.

Evidence on Effectiveness

The empirical evidence on IoT's agricultural benefits has grown substantially since 2023 and now allows for reasonably specific, if still context-dependent, estimates of effect. On water use, systematic reviews of IoT-enabled smart irrigation report water savings ranging from roughly nine to fifty percent relative to conventional irrigation practices, with most studies reporting savings accompanied by maintained or improved yields of approximately five to twenty-five percent rather than yield loss (Moustafa et al., 2026) ^[3]. Individual field studies cited within this literature illustrate the underlying mechanism: in one multi-season wheat study, an IoT-guided deficit-irrigation treatment using twenty-four and a half percent less water than a standard evapotranspiration-based schedule maintained comparable yields while improving water productivity, demonstrating that precision soil-moisture monitoring can decouple water reduction from yield loss under the right conditions.

At the farm economic level, the most comprehensive quantitative synthesis to date—a meta-analysis integrating eighty-five empirical studies and 1,472 independent farm observations from around the world—found that precision agriculture technology adoption increases average return on investment by 22.3 percent and net profit by 18.5 percent (Lan & Ban, 2025) ^[1]. The same synthesis reports meaningful environmental co-benefits, including an average 15.1 percent improvement in nitrogen use efficiency, a 12.8 percent reduction in pesticide application, and a 9.4 percent reduction in greenhouse gas emissions. Importantly, this meta-analysis also identifies substantial heterogeneity in these effects: technology type, farm size, region, and development level all moderate outcomes, with variable-rate technology and auto-guidance systems showing the strongest benefits on large-scale grain farms, while benefits are comparatively weaker and less stable on small-scale farms and in developing-country contexts.

Reviews synthesizing outcomes across broader precision-agriculture technology categories similarly report gains in

the range of resource-use efficiency, yield stability, and cost reduction, though they caution that reported figures vary widely by crop, region, and study design, and recommend presenting outcomes as ranges rather than single point estimates to avoid overgeneralizing from favorable case studies. Taken together, this evidence indicates that IoT-enabled precision agriculture produces real, measurable resource-efficiency and economic gains on average, but that the magnitude of these gains is highly context-dependent and tends to favor larger, better-resourced operations over smallholder systems.

Barriers and Challenges to Implementation

High Costs and Limited Return for Smallholder Farmers

The most consistently cited barrier across the reviewed literature is the high upfront cost of IoT infrastructure, including sensors, microcontrollers, connectivity hardware, and associated installation and maintenance expenses. Reviews note that while IoT technologies demonstrate strong cost-saving potential and productivity gains over the long term, the initial capital outlay remains prohibitive for smallholder farmers operating on thin profit margins, a pattern reinforced by the finding that precision agriculture's economic benefits are markedly weaker and less stable on small-scale farms than on large commercial operations (Lan & Ban, 2025) ^[1]. This cost barrier is compounded by ongoing expenses for maintenance, repair, and specialized technical support that many smallholder operations are not equipped to absorb.

Rural Connectivity and Infrastructure Deficits

A second major barrier concerns inadequate rural connectivity and electrical infrastructure. Because IoT-based agricultural systems depend on reliable, real-time data transmission, unreliable internet access and inconsistent electricity supply in rural areas directly constrain system performance and reliability, disrupting the fast decision-making and automated resource management these systems are designed to enable. Studies focused on regions such as South Africa and Sub-Saharan Africa more broadly identify infrastructure deficits, including limited broadband penetration and rural electrification, as central obstacles to IoT deployment, alongside land fragmentation and low digital literacy among smallholder farmer populations.

Interoperability, Standardization, and Cybersecurity Gaps

A third recurring barrier involves the lack of interoperable standards across IoT platforms and devices, which complicates integration between sensor networks manufactured by different vendors and limits the scalability of pilot deployments into larger, unified systems. This is compounded by cybersecurity weaknesses: reviews of IoT-based irrigation automation specifically flag the need for stronger interoperability, standardization, and cybersecurity protocols as current gaps limiting fully autonomous, scalable irrigation management (Nsoh et al., 2024) ^[4]. More broadly, industry analyses of the global IoT device landscape note that manufacturers frequently prioritize cost and time-to-market over security in device design, a pattern with direct implications for agricultural systems that increasingly rely on billions of connected, often under-secured endpoints.

The Digital Divide and Uneven Global Adoption

Finally, the literature consistently documents an uneven global distribution of IoT innovation and adoption, described in one systematic review as a digital divide in which smallholder and resource-constrained farmers have substantially more limited access to smart-farming solutions than farmers in technologically advanced regions (Miller et al., 2025) ^[2]. Regional adoption studies reinforce this pattern: research on smallholder horticulture farmers in West Java found that limited access to electricity, irrigation infrastructure, and data connections created a persistent gap between available technology and the socio-ecological realities of small, fragmented landholdings, while comparable findings from Sub-Saharan Africa identify financial constraints, policy gaps, and limited farmer education as compounding barriers alongside infrastructure deficits.

Discussion and Implications

Taken together, this body of evidence suggests that IoT-enabled smart agriculture delivers real and increasingly well-documented benefits in water-use efficiency, yield stability, and farm profitability, but that these benefits are neither uniform nor automatically accessible to all farmers. The consistent finding that precision agriculture technologies generate stronger returns on large-scale, well-resourced operations than on smallholder farms implies that, without deliberate intervention, IoT adoption risks widening rather than narrowing productivity and income gaps within the agricultural sector. This carries a clear practical and policy implication: closing the digital divide identified across the reviewed literature will likely require targeted subsidies, shared-infrastructure models, and low-cost, low-power system designs specifically engineered for smallholder contexts, rather than reliance on the continued organic diffusion of technologies developed primarily for large commercial farms.

The persistence of interoperability and cybersecurity gaps alongside otherwise positive effectiveness evidence also implies that scalability and security cannot be treated as secondary concerns to be addressed after adoption accelerates. Establishing common data and communication standards across device manufacturers, and building baseline security practices into IoT hardware design rather than retrofitting them later, appear throughout the literature as prerequisites for moving from fragmented pilot deployments toward integrated, farm-wide, and eventually region-wide smart-agriculture systems. Similarly, the finding that infrastructure deficits—unreliable connectivity and electricity—constrain system performance suggests that IoT adoption strategies cannot be separated from broader rural infrastructure investment; agricultural technology policy and rural infrastructure policy are, in this sense, two sides of the same problem.

From a research perspective, the substantial heterogeneity documented across meta-analyses points to a need for more studies that explicitly report outcomes by farm size, region, and development level rather than presenting single pooled averages, so that practitioners and policymakers can better anticipate which contexts are likely to see the largest returns. Longer-term, multi-season field studies—of the kind already emerging in irrigation research—would also help clarify whether reported resource-efficiency and yield gains persist over time or diminish as novel systems age and require maintenance. Future research would additionally

benefit from more direct comparative work on affordable, edge-AI-based IoT architectures explicitly designed for resource-constrained farming systems, an area the current literature identifies as promising but still underdeveloped.

Conclusion

The literature reviewed here indicates that the Internet of Things has become a well-established and rapidly studied feature of modern agriculture, with accumulating evidence pointing to meaningful, measurable improvements in water-use efficiency, crop yield stability, input-use efficiency, and farm profitability. Applications spanning smart irrigation, environmental and soil sensing, AI-assisted crop and pest monitoring, and integrated farm automation each carry distinct benefits, and the evidence base quantifying these benefits has grown considerably since 2023, including large-scale meta-analytic work synthesizing findings across dozens of countries and crop systems. At the same time, unresolved challenges around cost, rural infrastructure, interoperability, cybersecurity, and an uneven global digital divide continue to constrain the technology's realized benefit, particularly for smallholder farmers. The weight of current evidence suggests that these challenges are best addressed not through further isolated technical innovation alone, but through deliberate attention to affordability, infrastructure investment, and standardization, so that the productivity and sustainability gains documented in the literature can be extended more equitably across the full range of farming contexts in which they are needed.

References

1. Lan J, Ban Q. The farm-level economic and environmental benefits of precision agriculture technology adoption: A meta-analysis of global evidence. *Sustainability*,2025;17(24):11223. <https://doi.org/10.3390/su172411223>
2. Miller T, Mikiciuk G, Durlik I, Mikiciuk M, Łobodzińska A, Śnieg M. The IoT and AI in agriculture: The time is now—A systematic review of smart sensing technologies. *Sensors*,2025;25(12):3583. <https://doi.org/10.3390/s25123583>
3. Moustafa A, Abdelwahab OMM, Ricci GF, Gentile F. Internet of Things-enabled smart irrigation systems for precision water management: A systematic review. *Agricultural Water Management*, 2026. Advance online publication. <https://doi.org/10.1016/j.agwat.2026.109497>
4. Nsoh B, Katimbo A, Guo H, Heeren DM, Nakabuye HN, Qiao X, et al. Internet of Things-based automated solutions utilizing machine learning for smart and real-time irrigation management: A review. *Sensors*,2024;24(23):7480. <https://doi.org/10.3390/s24237480>
5. Saha G, Shahrin F, Khan FH, Meshkat MM, Azad AAM. Smart IoT-driven precision agriculture: Land mapping, crop prediction, and irrigation system. *PLOS ONE*,2025;20(3):0319268. <https://doi.org/10.1371/journal.pone.0319268>
6. Sadiq MI, Wanke P, Azad MAK. Smart irrigation systems enabled with internet of things: A bibliometric review. *International Journal of Process Management and Benchmarking*,2024;16(1):111–125.