Integrating AI and Drone Technologies in Organic Crop Systems

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Summary

This narrative review examines the transformative role of artificial intelligence (AI) and drone technologies in organic crop production. Literature was identified through targeted searches in databases such as Scopus, Web of Science, Google Scholar, IEEE Xplore, and AGRIS, covering studies published between 2015 and July 2025, with emphasis on certified organic and low-input farming systems. AI-driven platforms enable real-time monitoring of soil moisture, nutrient levels, and water quality, supporting resource efficiency and sustainable practices. Drones enhance precision agriculture through soil organic carbon mapping and targeted delivery of beneficial insects, while block chain-integrated AI platforms strengthen certification transparency. Overall, these technologies demonstrate broad benefits including improved crop performance, reduced resource use, and enhanced compliance with organic standards. Key challenges remain, particularly high costs, technical expertise requirements, and regulatory gaps, which limit adoption among small-scale farmers. Future research should prioritize cost-effective, scalable solutions and standardized protocols to promote equitable access.

Key words

precision farming, organic agriculture, biological pest control, artificial intelligence, drone

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Introduction

With increasing awareness of the harmful consequences of conventional farming, organic agriculture has gained prominence as a more sustainable approach to cultivation. Unlike conventional agriculture, organic systems prioritize natural processes, prohibiting synthetic pesticides and fertilizers to maintain soil health, water quality, and ecosystem balance (Jiang et al., 2022; Van Bruggen et al., 2016). However, the labor-intensive nature of organic practices and the need for precise management to meet stringent certification standards have driven the adoption of advanced technologies. Artificial intelligence (AI) and unmanned aerial vehicles (UAVs), or drones, have emerged as transformative tools in organic crop production. These technologies pave the way for precision agriculture that aligns with organic principles while enhancing productivity and sustainability (Getahun et al., 2024; Kouadio et al., 2023). AI technologies, including machine learning (ML), neural networks, and sensor-based analytics, facilitate real-time monitoring of soil parameters (e.g., moisture, pH, nutrient content) and water quality (e.g., nitrate levels, salinity), critical for organic farming's emphasis on natural resource management (Abegunde & Obi, 2022). For instance, AI-driven systems can optimize irrigation and recommend organic amendments, reducing resource waste while maintaining soil fertility (Assimakopoulos et al., 2025). Similarly, drones equipped with multispectral and thermal sensors provide high-resolution data for soil and crop health assessment (Khan et al., 2024). These technologies support organic farmers in making data-driven decisions that enhance yields and comply with certification requirements (Bhakta et al., 2019; Borkhani et al., 2019; Imtiaz et al., 2025; Weraikat et al., 2025). In biological pest control, drones offer innovative solutions by delivering beneficial insects or organic agents, minimizing reliance on chemical interventions (Ivezić et al., 2023; Sathesh et al., 2024; I et al., 2025). AI-integrated drone systems enhance pest detection accuracy and lead to the reduction of crop losses (Alsadik et al., 2024; Bai et al., 2023). Nonetheless, tech-based organic farming still faces barriers, for instance high costs and technical demands, which weigh heavily on small-scale producers (Dhillon et al., 2023). This narrative review explores the applications of AI and drone technologies in organic or low-input agriculture. By synthesizing recent literature, this review aims to evaluate the benefits, challenges, and implications of these technologies and offer insights into their potential to revolutionize organic agriculture while addressing regulatory and practical considerations.

Material and Methods

The literature for this narrative review was identified through targeted searches in Scopus, Web of Science, Google Scholar, IEEE Xplore, and AGRIS, covering publications between 2015 and July 2025. We included peer-reviewed journal articles, conference proceedings, and major technical reports that addressed applications of AI and drone technologies in agriculture. Inclusion criteria prioritized studies conducted in certified organic systems or clearly defined low-input farming contexts. Conventional trials were considered only when their findings were directly relevant to organic practices (e.g., non-synthetic pest control methods or resource-efficient irrigation strategies). Non-English publications and studies focused exclusively on conventional, high-input systems without relevance to organic farming were excluded. For clarity, we define "organic" as farming systems that are formally certified under recognized standards (e.g., USDA, EU regulations), prohibiting synthetic inputs and emphasizing biodiversity and sustainability. The term "low-input" is used more broadly to describe agroecological approaches that minimize chemical use and prioritize ecological balance, even if not formally certified. When the term "organic" is used in this review, it refers strictly to certified systems unless otherwise specified. As a narrative review, this study synthesizes diverse perspectives but does not employ formal systematic screening or risk-of-bias assessment. While this approach allows for a broad and integrative overview, it may introduce selection bias and limits the generalizability of findings. These limitations are acknowledged and discussed further in the manuscript.

Literature Overview

AI Technologies in Organic Soil and Water Monitoring

AI, including ML, neural networks, and sensor-based analytics, facilitates real-time assessment of critical soil parameters such as moisture, pH, nutrient content and organic carbon, as well as water quality metrics like nitrate levels and salinity. These technologies enhance resource efficiency, reduce environmental impact, and support compliance with organic farming principles by minimizing reliance on synthetic inputs. One significant application of AI is in soil organic carbon (SOC) mapping, a key indicator of soil health. Ottoy et al. (2024) demonstrated the use of UAVs equipped with multispectral sensors to collect high-resolution data for SOC estimation in general agricultural parcels in Greece (not explicitly certified organic, but with clear transferability to organic systems through non-invasive methods). Their study employed mixed models to analyze spectral and topographical variables, achieving an 81 % explanation of SOC variation in that specific context (Ottoy et al., 2024). AI-driven soil nutrient analysis further supports organic farming by optimizing resource use. Lakshmi et al. (2024) developed an IoT-based platform integrating ML algorithms (CNNs and Random Forest) to analyze soil parameters. Their system recommends appropriate water and fertilizer quantities. By replacing time-consuming laboratory methods with real-time analytics, this approach ensures sustainable soil management. The prototype was tested on conventional farms, but its recommendations can be adapted to suggest only organic-approved amendments, thus showing high transferability to certified organic production (Lakshmi et al., 2024). Water quality monitoring is equally critical in organic systems. Gayathri et al. (2024) proposed an IoT-based application evaluated primarily in low-input farming scenarios. The system uses AI to monitor soil moisture and water quality in real time and employs sensors to detect nitrogen, phosphorus, and oxygen levels, recommending organic amendments to maintain water and soil health. Hence, it aligns directly with certification requirements (Gayathri et al., 2024). Vijayasuganthi et al. (2025) introduced the Fusion Enhanced Smart Farming System (FESFS), which combines Temporal Fusion Transformers (TFT) for time-series analysis and Graph Neural Networks (GNN) for spatial data analysis. When tested on low-input systems, it recorded a 25 % improvement in soil health indicators and a 30 % reduction in water usage in those particular trials. These results are promising but not necessarily universally replicable across all soil types, climates, or management regimes, or certification schemes (Vijayasuganthi et al., 2025).

Drone Applications in Biological Pest Control

A key application of drones as active intervention systems is the automated delivery of beneficial insects, such as ladybugs or parasitoids, to combat pests without synthetic pesticides. Sathesh et al. (2024) introduced "Farmoline", a tethered-drone prototype for active spraying of organic pesticides and enzymes. This system uses a wired configuration with poles and pulleys to maintain stable flight paths, enabling precise application over large agricultural areas. By replacing chemical pesticides with natural agents, the system reduces environmental pollution and supports organic farming practices. However, it still remains an experimental system (not yet widely field-validated at commercial scale) with the technical feasibility of precise active delivery (Sathesh et al., 2024). In contrast, I et al. (2025) and Nadimpalli & Theja (2024) describe fully field-validated monitoring systems that have been tested under real farming conditions compatible with organic standards. I et al. (2025) proposed a smart crop-monitoring system that integrates drones with TensorFlow Lite–based deep learning models and high-resolution cameras; the platform captures aerial imagery, processes it on the fly, identifies pests and diseases with up to 98 % accuracy, and recommends only organic-compliant treatments. Similarly, Nadimpalli & Theja (2024) developed a drone-IoT system in which a multirotor drone equipped with triad spectroscopy and electrochemical gas sensors, paired with on-board AI, detects prohibited pesticide residues in real time with 93–96 % accuracy, distinguishing synthetic compounds from permitted organic substances. By combining these aerial data with continuous readings from ground-based IoT sensors and instantly uploading georeferenced results to a cloud dashboard, their system generates immediate compliance alerts and supplies direct, in-field evidence acceptable for organic certification audits. Asuka et al. (2024) developed an experimental semantic-segmentation model on an aqua-drone for weed detection in rice paddies (monitoring only). The system achieved a weed Intersection over Union (IoU) of 0.383 and a pixel accuracy of 0.970, demonstrating its effectiveness in identifying weeds for targeted biological control, such as introducing natural weed-suppressing organisms, thus reducing reliance on manual weeding (Asuka et al., 2024). Despite technical promise, several regulatory and practical constraints directly affect organic farmers: (i) national aviation authorities (e.g., FAA in the US, EASA in the EU) impose strict flight-altitude, line-of-sight, and no-fly-zone rules; (ii) many countries require certified remote-pilot licenses; (iii) battery life typically limits operations to 15–30 minutes per flight; and (iv) acquisition and maintenance costs remain prohibitive for most smallholder organic operations. These barriers often outweigh the ecological benefits unless subsidized or shared-service models are implemented.

Integration with Organic Certification Standards

The integration of AI and drone technologies into organic farming must align with specific, legally binding regulatory frameworks, notably USDA National Organic Program (7 CFR Part 205) (USDA, 2024) and Regulation (EU) 2018/848 (European Union, 2018) together with its implementing and delegated acts in the European Union. Both regimes explicitly require verifiable records of all inputs, field operations, buffer-zone management, and absence of prohibited substances. AI and drone technologies can realistically support three key pillars of organic certification compliance. Firstly, they enable robust input traceability by automatically recording which fertilizers, soil amendments, or pest-control products were recommended or applied, ensuring that only substances approved under USDA NOP or EU Regulation 2018/848 are used. Secondly, they generate automated, georeferenced field-operation logs, including date, time, GPS coordinates, and volume data for every irrigation cycle, drone flight, or release of biological agents, creating auditable digital records that replace or supplement traditional paper-based documentation. Thirdly, integrated sensors provide real-time or near-real-time residue monitoring, allowing rapid detection of prohibited synthetic substances directly in the field and thereby complementing (though not yet fully replacing) the mandatory laboratory residue testing required by both USDA and EU organic standards. These capabilities deliver verifiable, tamper-resistant evidence that significantly strengthens the certification process. In one approach, Imtiaz et al. (2025) developed an IoT-driven platform that combines smart sensors with permissioned block chain to monitor temperature, humidity, and pesticide levels. The system creates tamper-proof logs acceptable to both USDA NOP and EU certifiers, achieving 92 % fraud-detection accuracy and reducing verification latency by 40 % in their trials, thereby strengthening input traceability and audit readiness (Imtiaz et al., 2025). Drones also contribute directly to compliance. As mentioned in the previous section, Sathesh et al. (2024) introduced "Farmoline," a tethered drone system applying only certified-organic pesticides and enzymes; its flight and spraying data can be automatically logged, providing auditable evidence that no prohibited synthetic substances were used, in full accordance with §205.206 (USDA NOP) and Article 9(3) of EU 2018/848 (Sathesh et al., 2024). Similarly, Gayathri et al. (2024) demonstrated an AI–IoT application that recommends only approved organic amendments (e.g., compost, manure, rock phosphate) and records every recommendation, supporting the restricted-substances documentation required during certification inspections (Gayathri et al., 2024). A frequently overlooked but critical issue is data ownership and governance in AI- and drone-enabled organic farming (Dembani et al., 2025). Under current legal frameworks, such as the General Data Protection Regulation (GDPR) in the European Union (European Union, 2016) and the voluntary Privacy and Security Principles for Farm Data in the United States (Kaur et al., 2022), the farmer remains the data controller and legal owner of all farm-generated data, including sensor, drone, and AI-derived datasets (Kaur et al., 2022). However, many cloud-based AI and drone-service providers retain broad, often perpetual access rights for analytics, model retraining, or third-party sharing through standard service agreements, creating risks of commercial exploitation of sensitive production data and potential conflicts with organic certification audits that require verifiable, farmer-controlled records (Sinha & Dhanalakshmi, 2025). Transparent, farmer-centric solutions, such as permissioned block chain ledgers for immutable traceability and federated-learning architectures that keep raw data on-farm while sharing only aggregated model updates, are increasingly recommended to preserve privacy, prevent data lock-in, and enable controlled, audit-specific sharing with accredited certifiers without compromising organic principles (Ababio et al., 2025; Sinha & Dhanalakshmi, 2025). We must acknowledge that challenges persist: high costs, lack of standardized technology protocols in organic regulations, and limited digital infrastructure in rural areas continue to restrict adoption, especially among small-scale operators (Petrovic et al., 2025). Until organic regulations explicitly recognize digital logs and sensor-based residue evidence as sufficient for certain compliance checks, these tools will remain supplementary rather than substitutive. When properly governed and aligned with USDA NOP, EU 2018/848, and equivalent standards worldwide, AI and drone technologies can significantly strengthen traceability, reduce audit burden, and enhance the credibility of organic certification, provided cost, training, regulatory recognition, and robust data-governance policies are addressed concurrently.

Discussion

The integration of AI and drone technologies into organic crop production offers substantial benefits, particularly in advancing sustainability, productivity, and compliance with organic certification standards. AI-driven systems, such as those described by Vijayasuganthi et al. (2025), enhance crop yields and reduce water usage through precise monitoring and automated irrigation, aligning with organic farming's emphasis on resource efficiency. Similarly, drones like the Farmoline system developed by Sathesh et al. (2024) enable targeted delivery of organic pesticides and beneficial insects, thereby reducing environmental impact and supporting biodiversity, which is central to organic standards. These technologies also provide real-time data on soil health and pest activity. For example, I et al. (2025) reported a 98% accuracy rate in pest detection, which minimizes crop losses without reliance on synthetic inputs. Altogether, these innovations demonstrate how AI and drones are transforming organic farming by enabling precision agriculture that strengthens ecological principles. Recent studies further highlight the implications of these technologies for organic farming practices. Gayathri et al. (2024) showed how IoT-based AI systems can recommend organic amendments, promoting soil fertility and crop rotation while adhering to certification requirements. Such systems reduce reliance on manual labor and improve decision-making, allowing farmers to optimize resource use. Drones also support non-invasive pest control, as demonstrated by Asuka et al. (2024), where weed detection in rice paddies facilitated biological control methods and reduced chemical dependency. These advancements clearly strengthen organic farming's sustainability by minimizing environmental degradation and supporting long-term soil health (Van Bruggen et al., 2016). Nevertheless, integration must remain consistent with organic principles. Over-mechanization risks disrupting natural ecosystems, making it essential that AI and drone applications prioritize biodiversity and soil integrity. Despite promising results, a critical examination of the evidence reveals that most reported performance gains remain provisional and context-specific. Improvements in water-use efficiency (30%), soil-health indicators (25%), pest-detection accuracy (93–98%), and fraud-detection rates (92%) largely originate from small-scale experiments, controlled trials, or early-stage prototypes conducted on conventional or low-input farms rather than certified organic systems exposed to real-world variability in soil type, climate, weed pressure, and pest complexes (Vijayasuganthi et al., 2025; I et al., 2025; Imtiaz et al., 2025; Nadimpalli & Theja, 2024). To date, very few technologies have undergone multi-season, multi-site validation under the diverse agroecological and regulatory conditions that characterize commercial organic production across different continents. Consequently, the scalability and transferability of these gains to certified organic farms remain uncertain and require substantially more robust, long-term field testing before broad recommendations can be made. Beyond technical maturity, socio-economic constraints severely limit equitable adoption, particularly among smallholder and resource-constrained farmers who constitute the majority of the global organic sector. High upfront costs for drones, sensors, high-resolution imagery, cloud subscriptions, and on-board computing platforms routinely exceed US $10,000–50,000 per farm unit, placing them far beyond the financial reach of most small-scale organic producers (Petrovic et al., 2025; Dhillon & Moncur, 2023). Access to reliable rural internet, electricity, and spare parts further compounds the challenge in many organic farming regions. Equally important is the persistent digital-skills gap: operating UAVs, interpreting AI-derived recommendations, and maintaining data-security protocols demand levels of technical literacy and ongoing support that are often unavailable without dedicated extension services or cooperative technology-sharing programs (Bashiru et al., 2024; Borkhani & Mohammadi, 2019). Without targeted subsidies, cooperative ownership models, open-source software initiatives, or public–private training partnerships, there is a significant risk that AI and drone technologies will exacerbate existing inequalities rather than reduce them. Several limitations of current research must also be acknowledged to contextualize applicability. Some studies, such as Petrovic et al. (2025), rely on survey-based data to assess technology adoption, which may introduce response biases and limit generalizability. Regional focus is another constraint: research centered on Visegrad countries may not reflect challenges in tropical or developing regions, where infrastructure and economic barriers are more pronounced. Moreover, systems like Farmoline (Sathesh et al., 2024) or the Fusion Enhanced Smart Farming System (Vijayasuganthi et al., 2025) require substantial investment and training, potentially excluding marginalized farming communities. The literature selection in this review, restricted to English-language publications from 2015 to July 2025, may also overlook relevant non-English studies or earlier foundational work. Finally, regulatory and data security challenges remain underexplored. While Imtiaz et al. (2025) address block chain for certification transparency, the lack of standardized protocols for drone and AI use complicates compliance with organic standards (Narzari et al., 2025). Future research should therefore focus on addressing the challenges of cost, accessibility, and scalability to make AI and drone technologies viable for small-scale organic farmers. Narzari et al. (2025) suggest developing standardized regulatory guidelines to facilitate adoption and ensure compliance with organic standards. Innovations in energy-efficient AI models and drone battery life, as proposed by Agrawal and Arafat (2024), could further enhance practicality. Additionally, exploring AI-driven predictive models for climate resilience, as suggested by Ukoba et al. (2024), could help organic farmers adapt to changing environmental conditions. Collaborative efforts between researchers, policymakers, and certification bodies are essential to refine these technologies and integrate them seamlessly into organic farming systems.

Conclusion

AI and drone technologies offer clear potential to enhance precision in organic crop production, with documented significant gains in resource efficiency, pest-detection accuracy, and certification transparency in the reviewed studies. However, these results derive almost exclusively from small-scale, early-stage, or non-organic trials conducted in recent years. Robust, multi-season validation under diverse certified organic systems remains largely absent, and high capital costs, rural connectivity deficits, and digital-skills gaps continue to restrict adoption, especially among smallholder farmers. Until scalable, affordable, and farmer-controlled solutions are developed and supported by targeted policy measures, the transformative impact of these technologies on global organic agriculture will remain limited. Future progress therefore depends on rigorous field testing in real organic contexts combined with inclusive financing, training, and data-governance frameworks.

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Mohammad Hossein Ghaedamini Asadabadi: Conceived the funding; Conceptualization; Writing first draft and final version of the manuscript.

Declaration of Competing Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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