AUREVIAJ JOURNAL OF NATURAL SCIENCES
https://aureviaj.com/ajns/article/view/11

AUREVIAJ

Article | Open Access

The Use of Drones in Agriculture: Applications, Benefits, Challenges, and Prospects for Precision Farming

Olumide Awolowo*

Alumnus, Faculty of Agriculture, University of Nigeria, Nsukka, Nigeria

ABSTRACT

The rapid development of unmanned aerial vehicle (UAV) technology has created new opportunities for improving agricultural production, crop monitoring, and resource management. Agricultural drones equipped with RGB, multispectral, hyperspectral, and thermal sensors can collect high-resolution information about crops and field conditions and provide data for precision-management decisions. This study reviews the existing literature on the use of drones in agriculture, focusing on crop monitoring, disease and pest detection, weed management, irrigation management, crop phenotyping, yield estimation, and pesticide and fertilizer application. A structured narrative literature-review approach was employed to synthesize findings from peer-reviewed studies addressing agricultural UAV applications and their associated benefits and limitations. The reviewed literature indicates that drones provide important advantages through their high spatial resolution, flexibility of deployment, and ability to collect information at critical stages of crop development. UAV-based remote sensing can assist in identifying crop stress, disease, weeds, water deficiency, and variations in crop growth, while spraying drones can facilitate the application of agricultural inputs in locations where conventional machinery may be difficult to operate. However, the literature also identifies significant technical, economic, environmental, and regulatory challenges. These include limited battery capacity, weather dependence, high equipment and processing costs, requirements for technical expertise, lack of standardized data-processing procedures, and concerns regarding pesticide spray drift. The findings suggest that drones are most effective when integrated with other precision-agriculture technologies and conventional agronomic knowledge rather than being treated as independent replacements for farmers or agricultural machinery. The study concludes that future developments in artificial intelligence, autonomous flight, sensor technology, data integration, and service-based models could increase the accessibility and effectiveness of agricultural drones.

Cite as: Awolowo, O. (2026). The Use of Drones in Agriculture: Applications, Benefits, Challenges, and Prospects for Precision Farming. *Aureviaj Journal of Natural Sciences. 1*(1), 1-13. https://aureviaj.com/ajns/article/view/11

ARTICLE HISTORY

Revised 3 Aug, 2026
Accepted 15 Aug, 2026

KEYWORDS

Agricultural drones, Crop monitoring, Precision agriculture, Remote sensing, Smart farming, Unmanned aerial vehicles, Multispectral imaging, Pesticide spraying

INTRODUCTION

Agriculture is undergoing a technological transformation driven by the increasing demand for food, pressure on natural resources, environmental concerns, and the need to improve production efficiency. Precision agriculture has emerged as an important approach for addressing these challenges by using digital technologies to identify and manage spatial and

***CONTACT** *Olumide Awolowo Alumnus, Faculty of Agriculture, University of Nigeria, Nsukka, Nigeria

temporal variability within agricultural fields. Within this broader technological transformation, unmanned aerial vehicles (UAVs), commonly known as drones, have become increasingly important tools for agricultural monitoring and management (Shafi et al., 2019; Tsouros et al., 2019).

Agricultural drones can carry a range of sensors, including RGB, multispectral, hyperspectral, and thermal cameras. These sensors enable the collection of detailed information about crop conditions at relatively high spatial and temporal resolutions. Unlike satellite imagery, UAVs can generally be deployed when specific information is required and can operate at low altitudes to produce very detailed imagery. The flexibility and high spatial resolution of UAV systems have consequently made them attractive for precision-agriculture applications (Pádua et al., 2020; Tsouros et al., 2019).

The application of UAVs in agriculture has expanded considerably beyond conventional aerial photography. Research has identified applications including crop-growth monitoring, yield estimation, disease detection, weed mapping, irrigation management, nutrient assessment, crop phenotyping, and pesticide application (Hassler & Baysal-Gurel, 2019; Olson & Anderson, 2021; Tsouros et al., 2019). The data collected by UAVs can subsequently be processed using geographic information systems (GIS), photogrammetric techniques, vegetation indices, machine-learning algorithms, and other analytical methods.

One of the major advantages of UAV-based agricultural monitoring is its ability to provide spatially detailed information. Traditional field scouting can require substantial labor and may not adequately capture variability across large fields. UAV imagery can provide farmers and agricultural professionals with a visual representation of crop conditions and can identify areas requiring further investigation (Olson & Anderson, 2021). Tsouros et al. (2019) noted that UAVs can support precision agriculture by providing information that helps determine where and when agricultural inputs should be applied.

The type of sensor used by a drone determines the type of agricultural information that can be obtained. RGB cameras can provide high-resolution visible imagery, whereas multispectral and hyperspectral sensors can capture wavelengths beyond the visible spectrum. Such imagery can be used to calculate vegetation indices and identify differences in crop vigor that may not be immediately apparent to human observers (Adão et al., 2017; Pádua et al., 2020). Thermal sensors provide another source of information because variations in canopy temperature can be associated with plant water status and stress (Messina & Modica, 2020).

Disease and pest detection represents another important application. Crop diseases and pest infestations can vary considerably across a field, making uniform treatment inefficient in some circumstances. UAV imagery can help identify areas showing abnormal vegetation characteristics and consequently support targeted field inspection and intervention (Hafeez et al., 2023; Sankaran et al., 2015). The integration of UAV imagery with artificial intelligence and deep-learning algorithms has further expanded the potential for automated crop classification, disease recognition, weed detection, and other agricultural applications (Kamilaris & Prenafeta-Boldú, 2018).

Drones are also increasingly used for agricultural spraying. UAV sprayers can apply pesticides and other agricultural inputs without requiring conventional tractor-mounted equipment. This may be particularly useful in difficult terrain, wet fields, densely planted crops, or situations where conventional machinery could damage crops. Hafeez et al. (2023) identified crop monitoring and pesticide spraying among the principal applications of agricultural drone technology.

However, the use of drones for pesticide application also presents environmental challenges. Spray drift is affected by droplet size, wind speed, flight height, flight speed, and other operational parameters. Wang et al. (2020), for example, demonstrated that spray drift from UAV systems varied with wind speed and droplet size. Their findings indicate that UAV spraying requires appropriate operational controls and cannot simply be assumed to be environmentally risk-free. More recent experimental work has continued to investigate the effects of flight and spray parameters on UAV spray deposition and off-target movement (Li et al., 2026).

Another challenge concerns the processing and interpretation of UAV data. Although drones can collect large amounts of high-resolution information, raw imagery does not automatically translate into useful agricultural decisions. Image processing, calibration, classification, and interpretation require specialized knowledge and appropriate analytical methods. Tsouros et al. (2019) identified the lack of standardized workflows for UAV data acquisition and processing as an important challenge affecting the broader adoption of UAV technology in precision agriculture.

Economic considerations are equally important. The cost of UAV platforms, specialized sensors, batteries, software, maintenance, operator training, and data processing can limit adoption, particularly among small-scale farmers. Consequently, the economic value of agricultural drones depends on factors such as farm size, crop type, frequency of use, labor costs, and the availability of alternative technologies (Olson & Anderson, 2021).

Although the literature demonstrates considerable potential, the effectiveness of drones should therefore be evaluated within the broader agricultural system. UAVs are primarily information-collection and application technologies; their value depends on how accurately the resulting information is interpreted and incorporated into agricultural decision-making. As Olson and Anderson (2021) argued, UAV-derived analyses can contribute to improved input efficiency and reduced environmental impacts, but successful implementation depends on appropriate technologies and management practices.

Against this background, the present study reviews the major applications, benefits, and challenges associated with agricultural drones and considers their future role in precision farming.

Accordingly, this study addresses the following research questions:

1. What are the principal applications of drone technology in modern agriculture?
2. What benefits can agricultural drones provide for crop monitoring and farm management?

3. What technical, economic, environmental, and regulatory challenges limit the adoption of agricultural drones?

RESEARCH METHODOLOGY

Research Design

This study employed a structured narrative literature-review design. A literature-review methodology was considered appropriate because the purpose of the study was to synthesize existing scholarly evidence concerning agricultural UAV applications, benefits, limitations, and future developments rather than to report the results of a new field experiment.

Literature reviews are particularly useful in rapidly developing technological fields because they enable researchers to identify major application areas, compare findings across studies, and identify unresolved research problems. Previous reviews have demonstrated that UAV research in agriculture encompasses a wide range of applications and technologies, including remote sensing, crop monitoring, disease detection, irrigation management, and pesticide application (Hassler & Baysal-Gurel, 2019; Olson & Anderson, 2021; Tsouros et al., 2019).

Search Strategy

Relevant scholarly literature was identified using combinations of keywords including *agricultural drones*, *unmanned aerial vehicles agriculture*, *UAV precision agriculture*, *drone crop monitoring*, *UAV disease detection*, *UAV irrigation*, *UAV pesticide spraying*, *multispectral UAV agriculture*, *thermal UAV agriculture*, and *artificial intelligence agriculture*.

The review included peer-reviewed journal articles addressing the use of UAVs in crop production and agricultural management. Both review articles and empirical studies were considered because review studies provide an overview of the field, whereas empirical studies provide evidence concerning specific UAV applications and operational outcomes.

Selection and Analysis

Studies were included when they:

- examined UAV or drone technology in agriculture;
- addressed crop production, crop monitoring, resource management, or agricultural input application;
- presented empirical findings, systematic or narrative reviews, or technological analyses relevant to agricultural UAVs; and
- contributed to answering at least one of the research questions.

Studies unrelated to agricultural applications were excluded.

The selected literature was analyzed thematically. Five major themes emerged:

1. crop monitoring and field mapping;
2. disease, pest, and weed detection;

3. irrigation and resource management;
4. spraying and agricultural input application; and
5. technical, economic, environmental, and regulatory challenges.

RESULTS

Crop Monitoring and Field Mapping

The literature consistently identifies crop monitoring as one of the most established and widely deployed applications of UAV technology in modern precision agriculture. Drones provide high-resolution aerial imagery that allows growers and agronomists to continuously monitor crop growth dynamics, canopy architecture, leaf area index, crop coverage, and spatial variability across large agricultural fields (Pádua et al., 2020; Tsouros et al., 2019). Standard red-green-blue (RGB) cameras provide high-definition visual imagery useful for preliminary field inspection, boundary mapping, and assessing basic crop emergence. However, the integration of advanced multispectral and hyperspectral sensors expands these capabilities by capturing specific narrow bands across the visible, near-infrared (NIR), and short-wave infrared (SWIR) spectra. These spectral reflections are used to calculate mathematical vegetation indices—most notably the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), and the Normalized Difference Red Edge (NDRE) index—which quantify variations in plant vigor, chlorophyll concentration, and photosynthetically active radiation absorption across distinct management zones (Adão et al., 2017; Olson & Anderson, 2021).

The sub-centimeter spatial resolution afforded by UAV platforms is particularly advantageous when dealing with within-field spatial heterogeneity driven by soil texture variations, micro-topography, or localized drainage issues. Rather than treating an entire field as a single, uniform management unit using blanket treatments, farm managers can segment fields into discrete vigor zones and target specific areas requiring physical inspection or localized nutrient application. This spatially variable approach aligns directly with the core objective of precision agriculture: delivering the right input, at the right rate, at the right place, and at the right time (Shafi et al., 2019; Tsouros et al., 2019). Nevertheless, spectral vegetation indices reflect plant physiological stress in a non-specific manner. A localized drop in NDVI or greenness may be triggered by nitrogen deficiency, soil compaction, root rot, fungal infections, pest feeding, salinity, or waterlogging. Because UAV imagery identifies the presence and spatial extent of stress without revealing its underlying etiology, researchers consistently emphasize that remote sensing observations must be paired with ground-truthing, physical soil and tissue sampling, and expert agronomic knowledge (Olson & Anderson, 2021).

Disease and Pest Detection

Early disease and pest detection represents another critical application where UAVs offer clear efficiency gains over manual scouting. Plant diseases and insect infestations rarely affect fields uniformly; instead, they originate as localized hotspots or spread along environmental gradients such as prevailing winds, irrigation lines, or field borders. UAV-based imaging allows operators to rapidly scan vast acreages, map the spatial patterns of stress outbreaks, and direct field scouts precisely to affected zones before severe crop loss occurs (Hafeez et al., 2023; Sankaran et al., 2015). Multispectral and hyperspectral payloads are instrumental in this domain because pathogen attacks and pest damage induce physiological changes—such as stomatal closure, breakdown of leaf pigments, altered leaf tissue structure, and reduced water content—that alter light reflectance in the red-edge and near-infrared regions long before visible symptoms like necrosis or chlorosis appear to the human eye (Adão et al., 2017; Pádua et al., 2020).

The integration of artificial intelligence has significantly elevated the diagnostic utility of UAV data. Machine-learning algorithms and deep learning architectures—such as Convolutional Neural Networks (CNNs) and semantic segmentation networks—are routinely trained on high-resolution UAV imagery to automate plant species classification, leaf lesion recognition, viral symptom detection, and pest-induced defoliation scoring (Kamilaris & Prenafeta-Boldú, 2018). These automated image-analysis pipelines can process thousands of high-resolution images rapidly, producing geo-referenced pest and disease intensity maps. However, the real-world accuracy and generalizability of automated detection models depend heavily on the diversity, balance, and quality of their training datasets. Models trained on a specific crop variety, growth stage, soil background, or atmospheric lighting condition frequently exhibit performance drops when applied to different cultivars, regions, or weather environments. Consequently, rigorous field validation and continuous model retraining remain necessary before automated UAV diagnostics can safely replace human expertise in operational decision-making.

Weed Detection and Management

Precision weed mapping is an essential UAV application aimed at minimizing herbicide use, lowering production costs, and mitigating environmental contamination. Weeds compete aggressively with agricultural crops for light, soil moisture, space, and essential nutrients, leading to substantial yield penalties if left unmanaged. Conventional weed control typically relies on broad-acre, uniform herbicide applications across entire fields, even when weed distribution is highly patchy or concentrated along field edges. UAV imagery captured during early crop development stages can map weed distribution with high spatial accuracy, enabling the generation of site-specific prescription maps that guide variable-rate or spot-spraying equipment (Tsouros et al., 2019).

To successfully distinguish weeds from cash crops, image processing algorithms rely on a combination of spectral signatures, textural features, spatial patterns, and row-geometry detection. For example, object-based image analysis (OBIA) and deep learning models can differentiate crop rows from inter-row vegetation, allowing early-emerging weeds to be identified even when they share similar spectral characteristics with the crop. Applying herbicides exclusively to infested management zones dramatically reduces total chemical volumes, decreases input expenses, and slows the development of herbicide-resistant weed populations. Nonetheless, the practical success of UAV weed detection depends on several technical variables, including flight altitude, sensor resolution, wind-induced canopy motion, crop growth stage, and the structural similarity between weed species and crop canopies. As a result, robust early-season weed discrimination across complex crop-weed mixtures remains an active area of research rather than a completely standardized, off-the-shelf commercial solution.

Irrigation and Water-Stress Management

Optimizing water management via UAV platforms is increasingly vital as climate variability intensifies and global agriculture continues to consume more than 70% of available freshwater resources. Precision irrigation strategies rely on identifying spatial variability in soil moisture and crop water availability to apply water selectively, prevent over-irrigation, reduce energy costs for pumping, and maintain yield potential (Shafi et al., 2019). Thermal sensors mounted on UAVs are particularly valuable in water-stress monitoring because plant canopy temperature acts as a direct indicator of stomatal conductance and transpiration cooling. Messina and Modica (2020) conducted a comprehensive review of UAV-based thermal remote sensing, highlighting crop water-stress index (CWSI) calculation, stomatal conductance mapping, and variable-rate irrigation scheduling as prime applications in precision agriculture.

When crops experience moisture deficits, they partially or fully close their stomata to prevent water loss, which reduces transpirational cooling and causes leaf surface temperatures to rise relative to ambient air temperature. UAV thermal imagery captures these micro-scale temperature shifts across the canopy, allowing farm managers to detect water stress days before visible wilting or pigment degradation occurs. By coupling UAV thermal data with multispectral indices and soil moisture sensor networks, growers can map field-level water deficits and adjust irrigation schedules accordingly. However, thermal readings are highly sensitive to fluctuating environmental factors, including ambient air temperature, wind velocity, relative humidity, solar radiation, and background soil exposure in sparse canopies. Ensuring reliable, repeatable thermal measurements requires rigorous radiometric calibration, atmospheric corrections, thermal flux modeling, and local meteorological contextualization (Messina & Modica, 2020).

Crop Phenotyping and Yield Estimation

In both plant breeding research and commercial field operations, UAVs have emerged as powerful tools for high-throughput phenotyping and yield forecasting. High-resolution multi-temporal imagery allows researchers, plant breeders, and agronomists to evaluate large numbers of field plots rapidly and non-destructively, extracting phenotypic traits such as canopy cover dynamics, leaf area index, plant emergence rates, flowering timing, and biomass accumulation (Olson & Anderson, 2021). Furthermore, by generating Digital Surface Models (DSMs) and Digital Elevation Models (DEMs) from overlapping RGB images via Structure-from-Motion (SfM) photogrammetry, UAV systems can measure plant height across successive growth stages with centimeter-level precision.

The ability to perform repeated, non-destructive flights throughout the growing season provides rich longitudinal datasets that capture how different plant genotypes respond to environmental stressors, soil variations, and different agronomic practices. These structural, temporal, and spectral features are increasingly integrated into empirical and machine-learning yield models to predict final crop yields weeks or months prior to harvest. However, yield forecasting remains a complex task because final crop yield is governed by non-linear interactions between genetics, environment, management practices, and seasonal weather events ($G \times E \times M$). Late-season heat waves, sudden pest outbreaks, hail damage, or lodging during grain fill can decouple early canopy vigor from final harvested yield. Consequently, UAV-based yield models require multi-year regional calibration and continuous validation against physical combine harvest data.

Pesticide and Fertilizer Application

The adaptation of multi-rotor UAV platforms into liquid application systems represents a major operational transition in agricultural mechanization. Agricultural spraying drones are equipped with liquid tanks, pumps, pressure or electrostatic nozzles, and flow meters, allowing them to apply liquid fertilizers, herbicides, fungicides, and insecticides directly to crop canopies. Spraying UAVs offer clear operational advantages in topographically challenging terrain—such as steep hillsides or terraced vineyards—as well as in waterlogged fields where heavy machinery would cause severe soil compaction or become stuck, and in high-canopy crops where ground sprayers inflict physical crop damage (Hafeez et al., 2023). Experimental evaluations have demonstrated that UAV sprayers can achieve effective canopy penetration and target deposition when operating under optimal flight parameters and nozzle configurations (Wang et al., 2019).

However, the application efficacy and environmental safety of drone spraying are governed by operational parameters. Factors such as flight altitude, travel speed, spray pressure, droplet size distribution, nozzle placement, and the downward airflow (downwash) generated by multi-rotor propellers dictate how droplets move through the air and land on target leaves. Operating outside recommended parameters can lead to off-target spray drift or uneven chemical distribution. Wang et al. (2020) demonstrated that spray drift risks increase significantly with higher ambient wind speeds, higher flight altitudes, and smaller droplet sizes, emphasizing the necessity of strict parameter control during operations. Recent comparative field studies by Li et al. (2026) evaluated droplet deposition, penetration depth, and off-target drift under varying wind conditions, comparing UAV application directly against traditional tractor-mounted boom sprayers. Their findings highlight that while UAV sprayers provide operational versatility, improper speed or height settings can exacerbate spray drift and reduce under-canopy deposition relative to ground rigs. Therefore, aerial spraying must be accompanied by accurate meteorological monitoring, appropriate nozzle selection, buffer zone management, droplet drift retardants, and adherence to local legal regulations.

Integration with Artificial Intelligence and Smart Agriculture

Recent literature increasingly frames agricultural UAVs not as standalone gadgets, but as integrated data-collection nodes within broader digital farming ecosystems and smart agriculture frameworks. UAVs act as an intermediate spatial link between coarse-resolution satellite observations and localized point measurements from ground sensors, supplying high-resolution datasets that feed into Geographic Information Systems (GIS), automated photogrammetry pipelines, cloud databases, and decision-support software (Hafeez et al., 2023; Tsouros et al., 2019). The application of deep learning algorithms has proved transformative for processing these large volumes of spatial data, enabling automated pattern recognition, feature extraction, leaf counting, yield estimation, and stress mapping (Kamilaris & Prenafeta-Boldú, 2018).

This convergence of UAV hardware, Internet of Things (IoT) field sensors, satellite streams, and artificial intelligence enables end-to-end automated workflows: an autonomous drone executes a pre-planned mission, uploads raw imagery to a cloud server, AI models process the data to detect crop anomalies, and variable-rate prescription files are pushed directly to smart farm machinery or spraying drones for immediate targeted action. Nevertheless, data handling, storage, and workflow standardization remain major operational bottlenecks across the industry. As Tsouros et al. (2019) noted, the lack of standardized operational protocols, inconsistent sensor calibration methods, variable atmospheric correction routines, and proprietary software ecosystems hinder the cross-comparability of scientific studies and present technical barriers to integrating UAV data seamlessly into commercial farm management information systems (FMIS).

DISCUSSION

The findings indicate that unmanned aerial vehicle (UAV) technology has developed into a multifunctional tool for precision agriculture. Its primary value lies not merely in its capacity to capture aerial imagery, but in its ability to generate spatially detailed information that directly informs agricultural decision-making. However, to fully understand the operational utility of drones, they must primarily be regarded as decision-support technologies rather than automated solutions. UAV imagery excels at identifying localized areas of abnormal crop development, yet it cannot independently determine the underlying agronomic cause. Reduced vegetation vigor, for instance, may stem from nutrient deficiencies, disease, pest infestation, water stress, or unfavorable soil conditions. Consequently, UAV technology is most effective when embedded within an integrated workflow—advancing from data collection, image processing, and anomaly detection to field verification, agronomic diagnosis, and targeted intervention. Olson and Anderson (2021) emphasized that while UAV-derived analyses support decisions regarding agricultural inputs, the ultimate utility of the technology relies heavily on ground verification and appropriate data interpretation.

This capability to map spatial variation underpins the potential of drones to improve input efficiency—a core tenet of precision agriculture, which seeks to apply the correct input at the right location, time, and quantity (Shafi et al., 2019; Tsouros et al., 2019). By pinpointing where water, fertilizers, herbicides, or pesticides are genuinely required, operational inputs can be applied selectively rather than uniformly. Nevertheless, technical capability does not automatically guarantee economic or environmental gains; the final outcome remains contingent on the accuracy of the underlying data, the validity of management recommendations, and the precision of the physical application.

The widespread adoption of UAVs is further conditioned by economic accessibility. The initial purchase price of an aircraft represents only a fraction of the total operational cost, which expands when accounting for specialized sensors, replacement batteries, analytical software, routine maintenance, data processing infrastructure, operator training, and regulatory compliance. These financial barriers are especially pronounced for smallholder farmers, for whom individual ownership of high-cost UAV systems is rarely economically rational. Addressing this constraint necessitates shared or service-based delivery models. Agricultural cooperatives, extension agencies, private service providers, and research institutions can offer centralized drone services to farmer collectives, making precision-agriculture tools accessible while ensuring specialized equipment is utilized at a frequency that justifies its capital cost.

Alongside economic factors, the environmental implications of agricultural UAVs present a nuanced picture. While precision monitoring supports optimized input management, UAV-based pesticide spraying introduces distinct environmental risks. As Wang et al. (2020) demonstrated, spray drift is strongly influenced by operational parameters such as ambient wind speed and droplet size distribution. Thus, the environmental footprint of UAV spraying depends on operational execution rather than the technology itself. Assuming that replacing tractor-mounted or manual sprayers with drones automatically mitigates environmental impacts is premature; actual chemical deposition is mediated by formulation, meteorological conditions, flight parameters, and nozzle specifications.

These operational constraints highlight broader technical limitations inherent to current UAV platforms. Limited battery endurance restricts flight times and coverage areas, while adverse weather compromises both operational safety and radiometric data quality. Furthermore, sensor selection and calibration directly dictate measurement accuracy. Beyond hardware constraints, data processing remains a substantial bottleneck. High-resolution UAV surveys yield massive datasets requiring specialized software, robust computing resources, and standardized analytical workflows. The absence of uniform acquisition and processing protocols currently limits cross-study comparability and longitudinal tracking (Tsouros et al., 2019). Successful implementation therefore demands an integrated framework encompassing hardware, software, technical skills, agronomic expertise, and standardized procedures.

Looking forward, the integration of artificial intelligence represents one of the most promising avenues for advancing UAV capability. Machine-learning and deep-learning architectures offer the potential to automate the identification of crop diseases, weed infestations, and abiotic stressors (Kamilaris & Prenafeta-Boldú, 2018). However, the real-world performance of these models depends on training datasets that adequately capture environmental heterogeneity. Because agricultural systems vary significantly across geographic regions, seasons, cultivars, soil types, and weather conditions, algorithms trained on localized data often struggle to generalize across different contexts. Future research must prioritize the development of robust, transferable AI models, standardized open-access datasets, and explainable frameworks, while integrating UAV data with ground observations, satellite imagery, Internet of Things (IoT) sensors, weather stations, and farm management information systems to construct truly comprehensive decision-support ecosystems (Bacco et al., 2021).

CONCLUSION

This literature review demonstrates that drones have become an important technological component of precision agriculture. Their applications extend from crop monitoring and field mapping to disease detection, weed management, irrigation assessment, crop phenotyping, yield estimation, and pesticide spraying (Hassler & Baysal-Gurel, 2019; Olson & Anderson, 2021; Tsouros et al., 2019).

The principal advantage of agricultural drones is their ability to collect high-resolution and spatially explicit information at flexible intervals. Multispectral, hyperspectral, and thermal sensors further expand their capacity to detect characteristics that cannot be reliably identified through ordinary visual observation (Adão et al., 2017; Messina & Modica, 2020).

The findings also indicate that UAVs can potentially improve the efficiency of agricultural management by helping identify areas that require specific interventions. However, this potential depends on the quality of the data and the ability of agricultural professionals to interpret those data correctly. Drones should therefore be considered decision-support technologies rather than replacements for farmers, agronomists, or conventional agricultural equipment.

Several challenges continue to limit wider adoption. These include equipment and operational costs, limited battery capacity, weather dependence, technical expertise, data-processing requirements, lack of standardized workflows, and regulatory requirements (Olson & Anderson, 2021; Tsouros et al., 2019). Pesticide spraying presents additional concerns regarding spray drift and environmental exposure (Wang et al., 2020).

The future of agricultural drones is likely to depend increasingly on their integration with artificial intelligence, IoT sensors, satellite remote sensing, GIS, and automated agricultural machinery. Such integration could transform UAVs from relatively simple aerial data-collection platforms into components of automated agricultural decision-making systems.

Future research should prioritize long-term field experiments, cost-benefit analyses, environmental assessments, standardized UAV data-processing procedures, cross-location validation of AI models, and studies examining the effectiveness of UAV technologies under smallholder farming conditions. Particular attention should also be given to service-based models that could make agricultural drone technology more accessible to farmers who cannot justify individual ownership.

Overall, the evidence suggests that drones have substantial potential to contribute to more precise, efficient, and data-driven agricultural production. Their long-term value, however, will depend not simply on technological advancement but on the successful integration of UAVs with sound agronomic practices, reliable data analysis, appropriate regulation, and economically viable agricultural systems.

REFERENCES

Adão, T., Hruška, J., Pádua, L., Bessa, J., Peres, E., Morais, R., & Sousa, J. J. (2017). Hyperspectral imaging: A review on UAV-based sensors, data processing and applications for agriculture and forestry. *Remote Sensing, 9*(11), 1110. https://doi.org/10.3390/rs9111110

Bacco, M., Barsocchi, P., Ferro, E., Gotta, A., & Ruggeri, M. (2021). Unmanned aerial vehicles for agriculture: An overview of IoT-based scenarios. In M. A. Imran, Q.

Abbasi, O. Onireti, & S. Ansari (Eds.), *Autonomous airborne wireless networks*. Wiley. https://doi.org/10.1002/9781119751717.ch11

Hafeez, A., Husain, M. A., Singh, S. P., Chauhan, A., Khan, M. T., Kumar, N., Chauhan, A., & Soni, S. K. (2023). Implementation of drone technology for farm monitoring & pesticide spraying: A review. *Information Processing in Agriculture*, *10*(2), 192–203. https://doi.org/10.1016/j.inpa.2022.02.002

Hassler, S. C., & Baysal-Gurel, F. (2019). Unmanned aircraft system (UAS) technology and applications in agriculture. *Agronomy*, *9*(10), 618. https://doi.org/10.3390/agronomy9100618

Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, *147*, 70–90. https://doi.org/10.1016/j.compag.2018.02.016

Li, Y., He, X., Zhu, Z., Quan, C., Fang, Z., Huang, Z., Liu, Z., Jiang, S., Wongsuk, S., He, M., & Wang, C. (2026). Spray drift evaluation from a four-axis unmanned aerial spraying system: Effects of spray parameters under different wind speeds and comparison with a boom sprayer. *Pest Management Science*, *82*(6), 5895–5910. https://doi.org/10.1002/ps.70691

Messina, G., & Modica, G. (2020). Applications of UAV thermal imagery in precision agriculture: State of the art and future research outlook. *Remote Sensing*, *12*(9), 1491. https://doi.org/10.3390/rs12091491

Olson, D., & Anderson, J. (2021). Review on unmanned aerial vehicles, remote sensors, imagery processing, and their applications in agriculture. *Agronomy Journal*, *113*(2), 971–992. https://doi.org/10.1002/agj2.20595

Pádua, L., Marques, P., Martins, L., Carreira, J., Dinis, J., Sousa, J. J., & Peres, E. (2020). UAV-based applications for precision agriculture: A systematic review. *Remote Sensing*, *12*, 1501.

Sankaran, S., Mishra, A., Ehsani, R., & Davis, C. (2015). A review of advanced techniques for detecting plant diseases. *Computers and Electronics in Agriculture*, *113*, 27–35. https://doi.org/10.1016/j.compag.2015.01.009

Shafi, U., Mumtaz, R., García-Nieto, J., Hassan, S. A., Zaidi, S. A. R., & Iqbal, N. (2019). Precision agriculture techniques and practices: From considerations to applications. *Sensors*, *19*(17), 3796. https://doi.org/10.3390/s19173796

Tsouros, D. C., Bibi, S., & Sarigiannidis, P. G. (2019). A review on UAV-based applications for precision agriculture. *Information*, *10*(11), 349. https://doi.org/10.3390/info10110349

Wang, G., Lan, Y., Qi, H., Chen, P., Hewitt, A., & Han, Y. (2019). Field evaluation of an unmanned aerial vehicle (UAV) sprayer: Effect of spray volume on deposition and the control of pests and disease in wheat. *Pest Management Science*, *75*(6), 1546–1555. https://doi.org/10.1002/ps.5321

Wang, G., Han, Y., Li, X., Andaloro, J., Chen, P., Hoffmann, W. C., Han, X., Chen, S., & Lan, Y. (2020). Field evaluation of spray drift and environmental impact using an agricultural unmanned aerial vehicle (UAV) sprayer. *Science of the Total Environment*, *737*, 139793. https://doi.org/10.1016/j.scitotenv.2020.139793