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Drone Technology in Crop Monitoring and Precision Agriculture

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ABSTRACT

The rapid advancement of unmanned aerial vehicle (UAV) technology has transformed modern agriculture by enabling real-time, high-resolution crop monitoring and precision farming practices. This review paper examines the current state of drone technology in agriculture, focusing on the types of drones employed, the sensors integrated for data acquisition, and the diverse applications in crop health assessment, pest and disease detection, precision spraying, irrigation management, and yield estimation. Drones equipped with multispectral, thermal, and hyperspectral sensors facilitate the computation of vegetation indices such as the Normalized Difference Vegetation Index (NDVI), enabling early detection of crop stress and nutrient deficiencies. The paper further discusses the integration of artificial intelligence and machine learning algorithms with drone-acquired data for intelligent decision-making. Despite significant benefits including enhanced efficiency, reduced chemical usage, and improved resource optimization, challenges such as high initial costs, regulatory constraints, limited battery life, and data processing complexities persist. The review concludes by highlighting future prospects for drone-based precision agriculture in achieving sustainable food production.

Keywords: *Precision Agriculture, Unmanned Aerial Vehicles, NDVI, Remote Sensing, Crop Monitoring.*

INTRODUCTION

Agriculture remains the backbone of the global economy, sustaining billions of people worldwide. However, the sector faces unprecedented challenges including climate change, water scarcity, soil degradation, and a growing global population projected to reach 9.7 billion by 2050 (Rejeb et al., 2022). These pressing challenges necessitate the adoption of innovative technologies that can enhance agricultural productivity while minimizing environmental impact. Precision agriculture, defined as the application of information technology and sensor-based systems to optimize farm management practices, has emerged as a key strategy for sustainable food production (Veroustraete, 2015).

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Among the most promising technologies driving precision agriculture is the use of unmanned aerial vehicles (UAVs), commonly known as drones. Drones offer a cost-effective, flexible, and efficient platform for acquiring high-resolution aerial data that was previously accessible only through expensive satellite imagery or manned aircraft (Mukherjee et al., 2019). The use of drones by corn, soybean, and wheat farmers alone could save an estimated $1.3 billion annually through increased crop yields and reduced input costs (Doering, 2015). The global agriculture drones market, estimated at USD 2.63 billion in 2025, is projected to reach USD 10.76 billion by 2030, growing at a compound annual growth rate (CAGR) of 32.6% (Markets and Markets, 2025).

This review paper provides a comprehensive examination of drone technology in crop monitoring and precision agriculture. It explores the types of drones and sensors used, key applications in crop health assessment and farm management, the role of vegetation indices in monitoring plant health, the integration of artificial intelligence, and the challenges and future prospects of this rapidly evolving technology.

Figure 1: Agricultural drone equipped with multispectral sensors conducting crop monitoring over a cultivated field

2. Types of Drones Used in Agriculture

Agricultural drones are broadly categorized into two primary types based on their design and flight mechanism: fixed-wing drones and multi-rotor drones. Each type possesses distinct characteristics that make it suitable for specific agricultural applications (Hu et al., 2022).

2.1 Fixed-Wing Drones

Fixed-wing drones resemble conventional aircraft with rigid wings that generate lift through forward motion. These drones are characterized by their longer flight times, typically ranging from 45 to 90 minutes, and their ability to cover large areas of up to 200 hectares in a single flight (Yang et al., 2017). Fixed-wing drones such as the eBee AG are particularly well-suited for large-scale field mapping, aerial surveying, and crop scouting over extensive farmland. However, they require a runway or catapult for take-off and landing, which limits their operational flexibility in confined or uneven terrain.

2.2 Multi-Rotor Drones

Multi-rotor drones, including quadcopters, hexacopters, and octocopters, utilize multiple propellers for vertical take-off and landing (VTOL). These drones offer superior manoeuvrability, the ability to hover at specific locations, and precise flight control, making them ideal for targeted crop inspection, precision spraying, and close-range monitoring tasks (Ahmad et al., 2022). The DJI Mavic 3M, a widely adopted multi-rotor agricultural drone, integrates a 20MP RGB camera with four 5MP multispectral sensors capable of capturing data in green, red, red-edge, and near-infrared bands, with flight times of up to 43 minutes.

Figure 2: Types of agricultural drones - Fixed-wing drone (left) and Multi-rotor quadcopter drone (right)

3. Sensors and Data Acquisition

The effectiveness of drone-based crop monitoring depends largely on the type and quality of sensors mounted on the UAV platform. Modern agricultural drones can carry a diverse array of sensors, each designed to capture specific types of information about crop conditions and field characteristics (Yang et al., 2017).

Table 1: Types of sensors used in agricultural drones and their applications

Sensor Type	Function	Application
RGB Camera	Captures visible light images in red, green, and blue bands	Visual crop inspection, plant counting, weed detection
Multispectral	Records reflectance across multiple spectral bands (green, red, red-edge, NIR)	NDVI computation, crop health assessment, nutrient stress mapping
Thermal Infrared	Measures surface temperature based on emitted thermal radiation	Water stress detection, irrigation management, disease identification
Hyperspectral	Captures data across hundreds of narrow, contiguous spectral bands	Detailed disease classification, soil composition analysis
LiDAR	Uses laser pulses to measure distances and create 3D point clouds	Canopy height mapping, terrain modelling, biomass estimation

Among these sensors, multispectral cameras are the most widely deployed in agricultural drone operations due to their lightweight design, cost-effectiveness, and ability to generate vegetation indices critical for precision agriculture (Frontiers, 2024). The data acquired by these sensors enables farmers to identify spatial variability within fields and make targeted management decisions.

4. Applications of Drone Technology in Agriculture

4.1 Crop Health Monitoring and Vegetation Indices

One of the most significant applications of drones in agriculture is the assessment of crop health through vegetation indices derived from multispectral imagery. The Normalized Difference Vegetation Index (NDVI) is the most widely used index, calculated using the difference in near-infrared (NIR) and red light reflectance: NDVI = (NIR - Red) / (NIR + Red). NDVI values range from -1 to +1, where values of +0.6 to +1.0 indicate very healthy, dense vegetation; values of +0.2 to +0.5 suggest moderate health; and values below +0.2 indicate stressed, sparse, or non-vegetated areas (Joshi, 2025). By generating NDVI maps from drone imagery, farmers can identify zones of crop stress, nutrient deficiency, or water stress that require targeted intervention.

In addition to NDVI, the Normalized Difference Red Edge (NDRE) index has gained prominence for detecting subtle changes in chlorophyll content, particularly at later crop growth stages when NDVI values tend to saturate (Singh & Misra, 2021). The combination of multiple vegetation indices provides a more comprehensive assessment of crop condition, enabling early detection of problems before they become visible to the naked eye.

Figure 3: NDVI-based crop health map showing spatial variability - Green (healthy), Yellow (moderate), Red (stressed)

4.2 Pest and Disease Detection

Drones equipped with multispectral and hyperspectral sensors can detect early signs of pest infestation and disease infection by capturing changes in spectral reflectance patterns of affected crops. When diseases attack crops, their colour, texture, and spectral characteristics change to a certain extent, and these changes can be detected by drone-mounted sensors before symptoms become visible to the human eye (Ren et al., 2020). The integration of deep learning algorithms with drone-acquired imagery has demonstrated remarkable capabilities in analysing and interpreting complex image data, enabling precise classification and detection of crop diseases and pests with classification accuracies exceeding 97% (Frontiers, 2024).

4.3 Precision Spraying

Precision spraying represents one of the most economically impactful applications of drone technology in agriculture. Spraying drones equipped with RTK-GPS precisely deliver pesticides, herbicides, fungicides, and fertilizers to targeted areas, significantly reducing waste and environmental impact compared to traditional broadcast methods (Qi et al., 2022). Modern agricultural spraying drones can cover up to 15-21 hectares per hour, dramatically decreasing application time while ensuring uniform coverage in dense crop canopies (DJI Agriculture, 2024). Variable-rate application (VRA) systems integrated with prescription maps derived from NDVI data enable site-specific application of inputs, optimizing resource use and reducing chemical contamination of soil and water resources.

Figure 4: Agricultural spraying drone performing precision pesticide application over crop field

4.4 Irrigation Management and Water Stress Assessment

Thermal infrared sensors mounted on drones enable the detection of canopy temperature variations that indicate water stress in crops. By generating thermal maps of agricultural fields, farmers can identify areas requiring irrigation and design more efficient water distribution systems. This capability is particularly valuable in water-scarce regions where optimising irrigation efficiency is critical for crop survival and yield maximisation (Veroustraete, 2015). Drone-derived data provides information to generate irrigation management zones, allowing for precision water application that reduces waste while maintaining optimal soil moisture levels.

4.5 Yield Estimation and Field Mapping

High-resolution drone imagery enables accurate estimation of crop yield prior to harvest, aiding farmers in market planning and resource allocation. By analysing temporal changes in vegetation indices and canopy characteristics throughout the growing season, predictive models can forecast yield with high precision. Additionally, drones equipped with LiDAR sensors create detailed three-dimensional maps of field topography, enabling farmers to plan field operations and optimise management strategies based on terrain variations (Ahmad et al., 2022). Stand counts and plant population assessments conducted through drone surveys are significantly more efficient compared to traditional manual counting methods.

5. Integration of AI and Machine Learning

The integration of artificial intelligence (AI) and machine learning (ML) algorithms with drone-acquired agricultural data represents a paradigm shift in farm management decision-making. AI-powered systems can process vast volumes of multispectral and hyperspectral data collected by drones, extracting meaningful features and generating actionable insights for farmers (Frontiers, 2024). Deep neural networks have demonstrated exceptional capabilities in classifying crop health conditions, identifying specific disease types, and predicting pest outbreaks with high accuracy. The combination of UAV remote sensing with AI enables a real-time, ground-space integrated platform for crop monitoring that is more efficient and cost-effective than traditional methods (Ren et al., 2020). Furthermore, AI-driven decision support systems can generate variable-rate prescription maps that synchronise with agricultural drones to execute precise spraying, fertilisation, and seeding operations automatically.

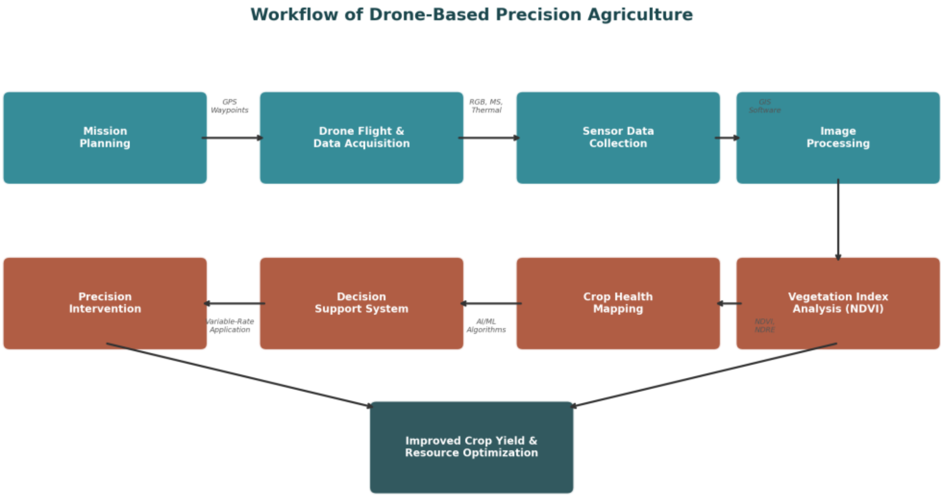

Figure 5: Workflow of drone-based precision agriculture from mission planning to crop yield improvement

6. Challenges and Limitations

Despite the numerous benefits of drone technology in agriculture, several challenges hinder its widespread adoption, particularly among smallholder farmers in developing countries.

High Initial Investment: The upfront cost of purchasing agricultural drones equipped with specialised sensors, along with supporting software, batteries, and maintenance expenses, represents a significant financial barrier for small and medium-sized farms (Hu et al., 2022).

Limited Battery Life and Flight Time: Most multi-rotor drones offer flight times of 20-45 minutes per battery charge, which limits the area that can be surveyed in a single mission and necessitates multiple flights for large farms (Yang et al., 2017).

Regulatory Constraints: Aviation regulations governing drone operations vary significantly across countries and jurisdictions. Restrictions on flight altitude, beyond-visual-line-of-sight (BVLOS) operations, and airspace permissions create compliance challenges for agricultural drone operators (Rejeb et al., 2022).

Data Processing Complexity: The large volumes of high-resolution data generated by drone sensors require significant computational power, storage capacity, and technical expertise for processing and interpretation, which may be overwhelming for farmers without a background in data analysis or geographic information systems (Mukherjee et al., 2019).

Weather Dependency: Drone operations are sensitive to adverse weather conditions including high winds, heavy rainfall, and extreme temperatures, which can limit the operational windows available for field surveys and spraying activities.

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All authors contributed to the critical revision and approved the final version of the manuscript.

CONCLUSION

Drone technology has emerged as a transformative tool in modern agriculture, offering unprecedented capabilities for real-time crop monitoring, precision input application, and data-driven farm management. The integration of advanced sensors, including multispectral, thermal, hyperspectral, and LiDAR systems, with sophisticated AI and machine learning algorithms enables farmers to detect crop stress, pest infestations, and disease outbreaks at early stages, facilitating timely and targeted interventions. Vegetation indices such as NDVI and NDRE derived from drone imagery provide quantitative assessments of crop health, enabling variable-rate management strategies that optimise resource utilisation while reducing environmental impact. The precision spraying capabilities of agricultural drones significantly reduce chemical usage and operational time compared to conventional methods, contributing to both economic savings and environmental sustainability. However, challenges including high acquisition costs, limited battery endurance, regulatory complexities, and data management requirements remain significant barriers to widespread adoption, particularly for smallholder farmers in developing regions. Addressing these challenges through technological innovation, supportive policy frameworks, affordable drone-as-a-service models, and capacity building programmes will be essential for realising the full potential of drone technology in achieving sustainable agricultural intensification and global food security. As the global agriculture drone market continues its rapid expansion, projected to exceed USD 10 billion by 2030, the integration of drones into mainstream farming practices will play an increasingly pivotal role in shaping the future of precision agriculture.

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