drones

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Review

Drones in Precision Agriculture: A Comprehensive Review of Applications, Technologies, and Challenges

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Abstract: In the face of growing challenges in modern agriculture, such as climate change, sustainable resource management, and food security, drones are emerging as essential tools for transforming precision agriculture. This systematic review, based on an in-depth analysis of recent scientific literature (2020–2024), provides a comprehensive synthesis of current drone applications in the agricultural sector, primarily focusing on studies from this period while including a few notable exceptions of particular interest. Our study examines in detail the technological advancements in drone systems, including innovative aerial platforms, cutting-edge multispectral and hyperspectral sensors, and advanced navigation and communication systems. We analyze diagnostic applications, such as crop monitoring and multispectral mapping, as well as interventional applications like precision spraying and drone-assisted seeding. The integration of artificial intelligence and IoTs in analyzing drone-collected data is highlighted, demonstrating significant improvements in early disease detection, yield estimation, and irrigation management. Specific case studies illustrate the effectiveness of drones in various crops, from viticulture to cereal cultivation. Despite these advancements, we identify several obstacles to widespread drone adoption, including regulatory, technological, and socio-economic challenges. This study particularly emphasizes the need to harmonize regulations on beyond visual line of sight (BVLOS) flights and improve economic accessibility for small-scale farmers. This review also identifies key opportunities for future research, including the use of drone swarms, improved energy autonomy, and the development of more sophisticated decision-support systems integrating drone data. In conclusion, we underscore the transformative potential of drones as a key technology for more sustainable, productive, and resilient agriculture in the face of global challenges in the 21st century, while highlighting the need for an integrated approach combining technological innovation, adapted policies, and farmer training.

Keywords: drones; precision agriculture; remote sensing; artificial intelligence; sustainable resource management; food security

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1. Introduction

Global agriculture faces unprecedented challenges in the 21st century [1], including population growth [2], climate change [3,4], and natural resource degradation [5]. These factors exert considerable pressure on existing agricultural systems, necessitating innovations to ensure food security and environmental sustainability.

Sustainable soil management has become a major concern worldwide. The authors of [6] emphasized the crucial importance of soils in achieving the United Nations Sustainable Development Goals (SDGs), highlighting their central role in food security, climate regulation, and biodiversity preservation. Yet, they also note that soil degradation is an urgent global problem, requiring the adoption of more sustainable agricultural practices.

Water management in agriculture represents a significant challenge, particularly in the context of climate change. The authors of [7] conducted a global assessment of agricultural water scarcity, considering the availability of "blue water" (rivers, lakes, groundwater, glaciers, and polar icecaps) and "greenwater" (held in plants, soil, and rain) under future climate change scenarios. Their study reveals that areas suffering from agricultural water scarcity are expected to expand considerably by the end of the 21st century, increasing from 34% to 84% of global cultivated areas in the most pessimistic scenario. Even in the most optimistic scenario, nearly half (48%) of global cultivated lands could face agricultural water scarcity. This situation is particularly alarming as it underscores the urgency of adopting more sustainable and water-efficient agricultural practices.

The impact of climate change on agriculture is already noticeable and is expected to intensify in the coming years. The authors of [8] have provided compelling evidence that climate change is already affecting global food production. Their analyses show that yields of some major crops, such as maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.), have already decreased in certain regions due to changes in temperature and precipitation patterns.

In this context, precision agriculture emerges as a promising approach to address these challenges. The authors of [9] emphasized the importance of reforming agricultural policies for climate change mitigation, highlighting the potential role of precision technologies. Drones are playing an increasingly important role in this field. Recent studies underscore the transformative potential of drone technology in agriculture. The authors of [10,11] demonstrated how drones can improve agricultural productivity through precise crop monitoring, targeted input application, and high-resolution data collection. These technologies offer the possibility of optimizing resource use, reducing agriculture's environmental impact, and improving the resilience of agricultural systems in the face of climate change. The applications of drones to agriculture are vast and constantly evolving. The authors of [12] provided a comprehensive review of multispectral imaging using UAVs for precision agriculture, highlighting their potential for early detection of crop stress, plant health mapping, and optimization of input management. The authors of [13] conducted an in-depth study on the application of digital technologies, including drones, in ensuring agricultural productivity and improving yields. The integration of artificial intelligence (AI) and the Internet of Things (IoTs) with drone technologies opens new perspectives for even more efficient and sustainable precision agriculture. These technological advances promise to revolutionize crop management, data-driven decision-making, and resource optimization in the agricultural sector. Yet, as the authors of [14] have pointed out, it is crucial to consider the ethical implications of using drones in agriculture and to develop a value-based framework to guide their deployment. The authors of [15] presented a comprehensive bibliometric review of the academic literature on agricultural drones, highlighting major research areas, such as remote sensing and precision agriculture, and identifying trends, research clusters, and future directions in this field.

This review aims to provide a comprehensive and up-to-date analysis regarding the use of drones in agriculture, addressing several important gaps in the existing literature. Our approach is distinguished by its holistic perspective, encompassing all applications of drones in the agricultural sector, unlike previous studies that have often focused on specific aspects. This global vision allows for a more complete understanding of the issues and opportunities that are related to this emerging technology. A crucial aspect of our study is the in-depth analysis of adoption challenges, a topic frequently neglected in previous reviews. By examining in detail the obstacles to the widespread adoption of drones, we seek to identify current barriers and potential solutions to accelerate the integration of this technology into current agricultural practices. This analysis is complemented by an interdisciplinary approach, integrating perspectives from agronomy, engineering, economics, and ethics, thereby offering a multidimensional understanding of the implications of using drones in agriculture. Our review emphasizes recent innovations, primarily covering the period 2020–2024. This focus on the most recent developments helps bridge the gap with older reviews and provides an up-to-date overview of the field, which is essential in a rapidly evolving sector. Beyond a simple inventory of applications, we propose a critical evaluation of economic and environmental impacts, based on recent empirical data. This in-depth analysis aims to provide a solid foundation for decision-making and guiding future research in the field.

The structure of this review is organized around eight main sections, each exploring a specific aspect of the use of drones in agriculture. We begin by explaining the adopted methodology, followed by a detailed presentation of drone systems that are used in this sector. The following sections successively examine diagnostic, interventional, and then combined and advanced applications, thereby offering a logical progression from understanding basic systems to the most sophisticated uses. We then address the challenges and perspectives of the field, before concluding with an in-depth analysis of economic and environmental impacts and a reflection on future directions for research and development in this field.

In sum, this review aspires to become a reference resource on the state of the art of drone use in agriculture. By addressing gaps that have been identified in the existing literature and offering a multidimensional perspective, we aim to provide a solid foundation for future research and applications in this constantly evolving field. Our goal is not only to inform but also to inspire new approaches and innovations in the use of drones for more efficient and sustainable agriculture.

2. Methodology

This systematic literature review on the utilization of drones in agriculture adheres to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, ensuring a rigorous, transparent, and reproducible approach [16].

2.1. Search Strategy

An extensive search was conducted across multiple reputable databases: MDPI, Springer, Google Scholar, and Scopus (Science Direct). The search terms "Drone AND agriculture", "Drone AND farming", "UAV AND agriculture", and "UAV AND farming" were consistently applied across all databases. The search primarily covered publications from January 2020 to September 2024, with exceptions made for particularly relevant earlier studies, especially in the field of regulations.

2.2. Inclusion and Exclusion Criteria

The review prioritized peer-reviewed articles published mainly between January 2020 and September 2024, with exceptions for seminal works or critical regulatory papers from earlier dates. Studies were included based on their direct relevance to drone applications in precision agriculture and their potential for generalizable insights. The selection process favored empirical studies, systematic reviews, and meta-analyses that provided substantive contributions to the field. Articles were excluded if they did not demonstrate a direct application or implications for agricultural drone use or lacked sufficient methodological rigor to support their conclusions.

2.3. Selection Process

The selection process consisted of three stages: initial screening of titles and abstracts, full-text review of pre-selected articles, and evaluation of the quality and relevance of retained studies. To ensure that duplicate entries were effectively managed, EndNote 21 software was utilized to identify and exclude duplicates during the initial screening phase.

2.4. Data Extraction and Synthesis

Key data extracted from each study included authors, year of publication, country of study, methodology employed, main results, and limitations. A narrative synthesis was conducted and organized according to the main themes identified. Each thematic section was generally developed using three different articles to ensure balanced and in-depth coverage of the subject.

2.5. Quality Assessment

The quality of the studies was evaluated based on content relevance and methodological rigor, publication date (prioritizing recent studies with justified exceptions), and geographic diversity to ensure the inclusion of studies from different regions worldwide.

2.6. Thematic Analysis

The research covered ten main themes: introduction and contribution of drone use in agriculture, drone systems, payload and sensors, platforms and software, diagnostic drones, specific applications, regulations, training, economic impact, and future perspectives and innovations.

2.7. Search Results

The initial search identified a total of 621 potentially relevant articles: MDPI (267), Springer (198), Google Scholar (46), and Scopus (115). After the rigorous selection process utilizing EndNote for duplicate management, 85 articles were included in the systematic review, representing a diversity of applications and geographical contexts. This methodology offers a comprehensive and structured overview of the article selection and analysis process while reflecting the diversity of themes and geographical contexts covered by this systematic review on the use of drones in agriculture. It addresses specific requirements mentioned earlier regarding theme-based selection, geographic diversity, and inclusion of relevant pre-2020 articles when necessary (Figure 1).

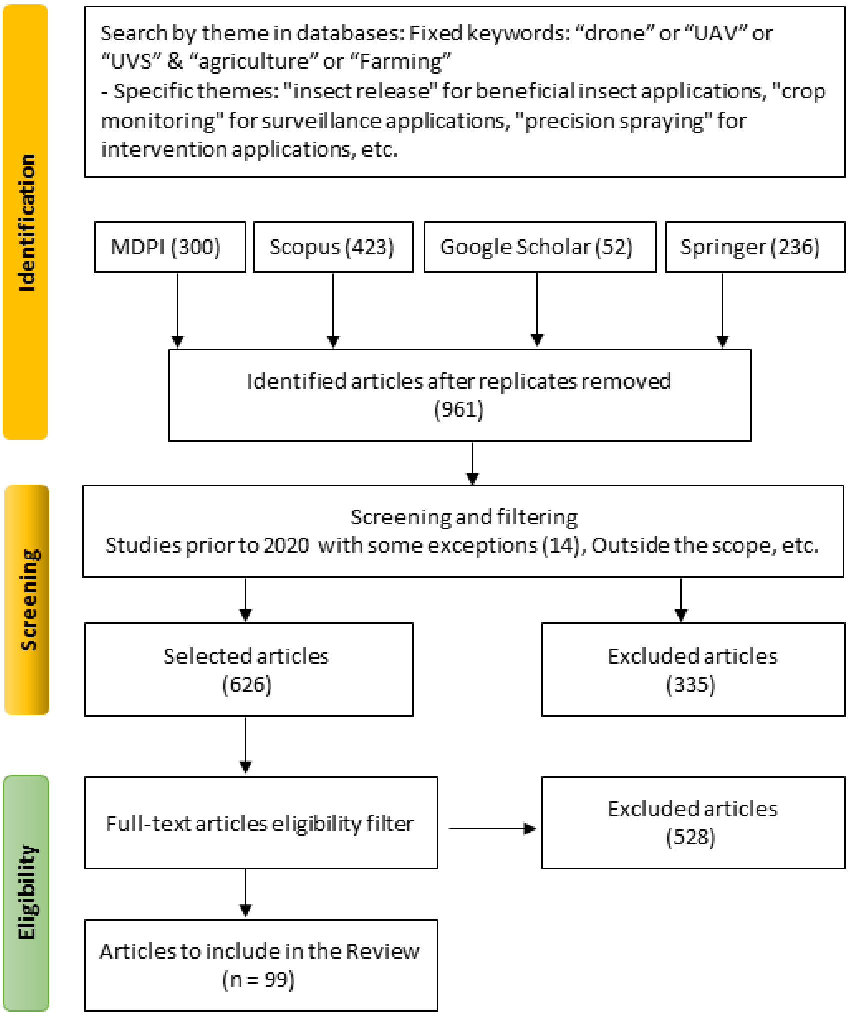

Figure 1. PRISMA flow diagram for the selection of articles on the use of drones in agriculture.

2.8. Synthesis and Summary Tables

At the end of each main section, a summary table was developed to synthesize the key information. These tables summarized the essential points of each section, highlighted recent technological advances, presented the main applications and their impacts, and identified challenges and perspectives. The tables were created by extracting and condensing the most relevant information from each section, focusing on quantitative data and significant results from the cited studies.

3. Drone Systems for Precision Agriculture

3.1. Evolution and Classification of Drones Used in Agriculture

3.1.1. Historical Development of Drones in Agriculture

The use of drones in agriculture has undergone rapid evolution since the 1980s. Initially, these unmanned aerial vehicles (UAVs) were primarily employed for military and civil surveillance and reconnaissance missions. The advent of digital technologies and advanced sensors in the early 2000s facilitated a broader adoption of drones in the agricultural sector. Contemporary drones are now capable of collecting precise data on crop health, resource management, and input optimization, rendering them essential tools for precision agriculture [17].

3.1.2. Classification of Drones Used in Agriculture

Agricultural drones can be categorized into several classes based on their design and operational mode:

1. Fixed-wing Drones:

These aircraft-like drones are engineered to cover extensive areas. Their capacity to operate at high altitudes enables the capture of high-resolution images over vast agricultural zones. They are particularly efficacious for large-scale mapping and surveillance missions [18].

2. Multirotor Drones:

Multirotor drones, such as quadcopters, offer enhanced maneuverability and hovering capabilities. They are optimal for applications requiring high precision, such as targeted spraying and detailed crop inspection. Their vertical take-off and landing capabilities make them suitable for use in challenging terrain [19].

3. Hybrid Drones:

The term "hybrid" in this context refers to drones that combine the features of both fixed-wing and multirotor platforms. These drones enable vertical take-off and landing while providing extended flight endurance. They are particularly advantageous for missions necessitating both extensive coverage and high precision [17].

4. Foldable-wing Drones:

These innovative drones offer enhanced portability while maintaining performance comparable to fixed-wing drones. They are designed for easy transportation and field deployment, making them particularly suitable for small- and medium-scale agricultural operations.

3.1.3. Performance Comparisons and Specific Applications

Each drone type exhibits specific advantages and limitations that are contingent upon the agricultural mission (Table 1). Fixed-wing drones are optimal for mapping large areas, whereas multirotor drones are more suitable for precision applications such as targeted spraying. Hybrid and eVTOL drones offer flexibility that renders them adaptable to a variety of applications, ranging from mapping to crop management [20].

Table 1. Comparison of different types of drones used in agriculture: advantages and disadvantages.

Drone Type	Advantages	Disadvantages
Fixed-wing drones	- Large surface coverage (up to 1000 ha/day) - High-altitude flight (up to 120 m legally) - Efficient for large-scale mapping - Long flight autonomy (1–2 h)	- Limited maneuverability - Requires a clear area for takeoff and landing - Less suitable for detailed inspections - Minimum speed required for flight
Multirotor drones	- High maneuverability - Hovering capability - Vertical takeoff and landing - Ideal for detailed inspections and targeted spraying	- Limited surface coverage (50–100 ha/day) - Shorter flight autonomy (20–30 min) - Less efficient for mapping large areas - More sensitive to strong winds
Hybrid and eVTOL drones	- Combines advantages of fixed-wing and multirotor - Vertical takeoff and landing - Good flight autonomy (up to 1 h) - Suitable for various missions	- Increased mechanical complexity - Higher cost - May require specific training for use
Foldable-wing drones	- Increased portability - Easy transport and deployment - Performance like fixed-wing drones - Suitable for small and medium-sized farms	- Potentially reduced durability due to folding mechanism - May have limited payload capacity - Potentially higher cost than standard models

3.2. Architecture of Drone Systems Used in Agriculture

3.2.1. Aerial Platform

The aerial platform constitutes the core of the agricultural drone system, integrating several essential components that determine its performance and capabilities [21].

Materials and Design

Modern drones are manufactured from lightweight and durable materials, such as carbon fiber composites, which optimize flight performance while reducing weight [22]. Aerodynamic designs are essential to improve energy efficiency and extend autonomy. Among the commonly used materials are carbon fiber or Kilver, widely used for its lightness and strength; aluminum, often used for the frame and certain structural parts; and composite materials, which combine fibers (such as carbon or glass) with resins. These materials are chosen for their ability to provide the necessary strength and durability while keeping the overall weight of the drone as low as possible, thus enhancing flight performance and efficiency.

Propulsion Systems (Electric, Hybrid, Combustion)

In this section, "hybrid" refers to propulsion systems that combine electric and combustion engines. Most agricultural drones use electric propulsion systems, offering a good balance between performance and ease of maintenance. However, for applications requiring extended autonomy, hybrid systems that combine electric and combustion engines are gaining popularity [23]. Commonly used battery types include lithium-polymer (LiPo), which is very common for its capacity/weight ratio; lithium-ion, which offers good energy density; and $LiFePO_4$ (Lithium ferrophosphate), which is safer but less energy dense. Innovative hybrid systems are also in development, such as electric-gasoline hybrids that combine a gasoline engine and electric motors, battery-fuel cell hybrids that use a hydrogen fuel cell in addition to batteries, and solar–electric hybrids that use solar panels to recharge batteries in flight. These diverse propulsion options allow for greater flexibility in drone design and application, catering to various agricultural needs and operating conditions.

Autonomy

Flight autonomy can vary, with drones capable of flying from 20 min to several hours, depending on usage conditions and payload. For the same drone, flight autonomy can fluctuate significantly depending on the weight of the payload, as heavier loads require more power and thus shorten flight duration. The payload capacity of agricultural drones varies considerably, ranging from a few hundred grams to several kilograms, depending on the size and type of drone. Flight autonomy can also vary, with drones capable of flying from 20 min to several hours, depending on usage conditions and load [24].

3.2.2. Navigation and Control Systems

Precision GPS/GNSS

High-precision satellite navigation systems are essential for precision agricultural operations. These systems allow drones to maintain their position with centimeter-level accuracy, which is crucial for precision agricultural applications [25].

Inertial Systems (IMU)

Inertial Measurement Units (IMUs) are used to stabilize drone flight and ensure precise navigation. By combining IMU data with GPS data, drones can correct their trajectory in real time, even under difficult flight conditions [26].

Anti-Collision and Obstacle Detection Systems

Obstacle detection systems, often based on LiDAR sensors or stereoscopic cameras, are increasingly integrated into agricultural drones to ensure operational safety. These systems allow drones to avoid collisions with obstacles, which is particularly important during autonomous flights in complex environments [27].

3.2.3. Communication Systems

Short and Long-Range Data Links

Drone communication systems use robust data links to ensure reliable control and real-time data transmission. These links can include typical frequencies of 2.4 GHz and 5.8 GHz, allowing stable communication, even in challenging environments [28].

Integration with 4G/5G Networks for BVLOS Operations

The integration of 4G and 5G networks allows drones to perform beyond visual line-of-sight (BVLOS) operations, significantly expanding their range and efficiency. This opens new possibilities for large-scale surveillance and application of phytosanitary products [29].

3.2.4. Ground Control Stations (GCS)

Hardware: Robust Computers, Screens, Control Interfaces

Modern ground control stations are equipped with powerful computers, high-resolution screens, and intuitive control interfaces. These stations allow operators to plan missions, monitor flights in real time, and process collected data [30].

Software: Mission Planning, Real-Time Processing, User Interface

Mission planning software is essential for optimizing drone operations. These tools allow the defining of flight trajectories, integration of weather data, and management of regulatory constraints. The authors of [31] highlighted the importance of this software for the efficient management of drone operations.

The following figure shows the block diagram of the drone system (Figure 2).

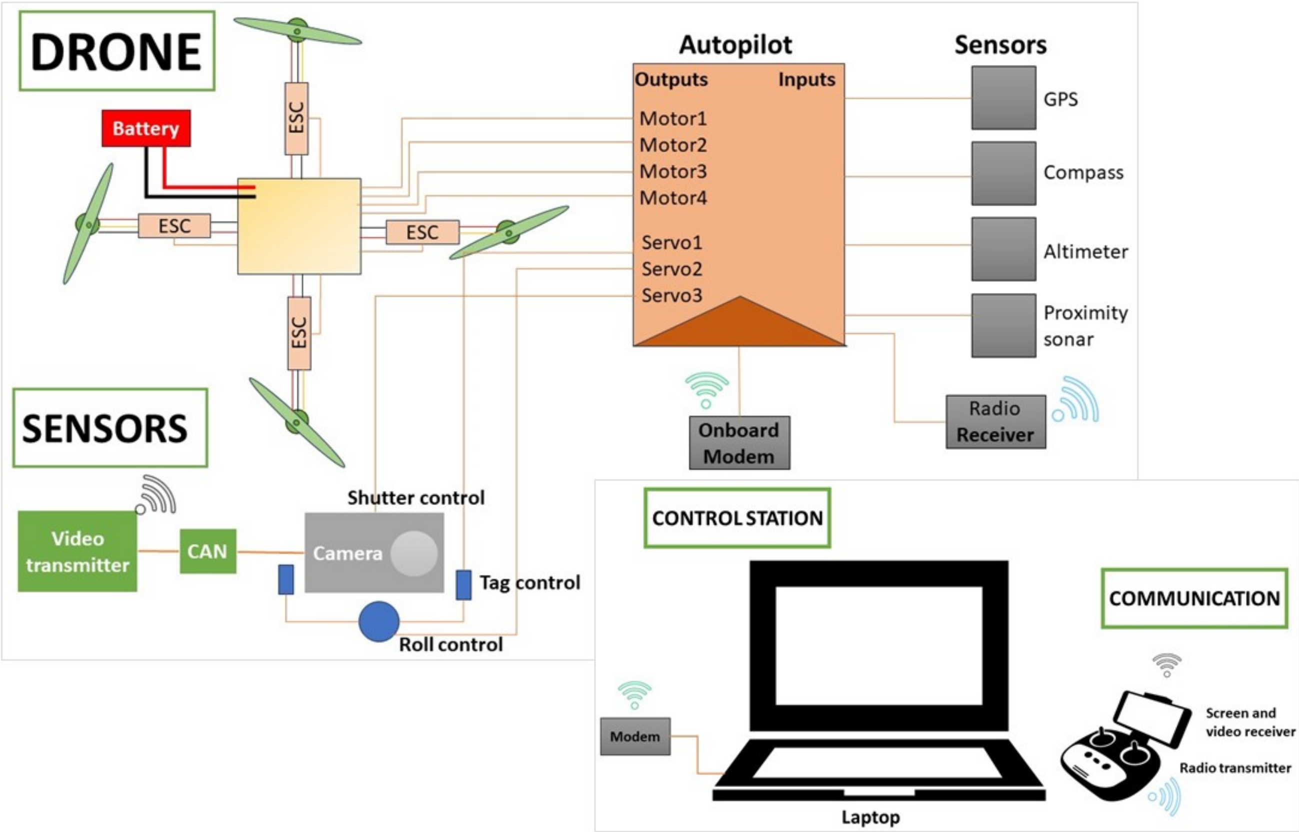

Figure 2. Block diagram of a drone system.

3.2.5. Payloads

Specialized sensors and payloads play a crucial role in the effectiveness of agricultural drones, enabling precise and varied data collection on crops and their environments. This section explores the different types of sensors that are used, emphasizing their contributions to plant health assessment and agricultural resource management.

Optical Imaging

High-resolution RGB cameras:

RGB (Red Green Blue) cameras are used for general mapping and visual inspection of crops. They capture visible light in the wavelengths of 400–700 nm. The authors of [32] demonstrated their utility in estimating potato plant densities with very high accuracy.

Multispectral and hyperspectral sensors:

Typical multispectral sensors capture 4 to 6 distinct spectral bands, generally in the visible (400–700 nm) and near-infrared (700–1000 nm) ranges. Hyperspectral sensors, in contrast, can capture hundreds of narrow bands, often covering a range from 400 to 2500 nm with a spectral resolution of 2–10 nm. These sensors are essential for assessing plant health and early stress detection. The authors of [33] provided a comprehensive review of the use of these sensors in precision agriculture, highlighting their ability to detect stresses that are not visible to the naked eye.

Thermal cameras:

Thermal cameras that are used in agriculture typically operate in the wavelength range of 7.5 to 14 µm (thermal infrared). They offer a typical thermal resolution of 0.05 °C to 0.1 °C, allowing for the detection of subtle temperature variations in crops. They are used for water stress detection and plant health assessment. The authors of [34] demonstrated their effectiveness in the early detection of crop water stress, enabling significant water savings.

LiDAR and 3D Mapping Systems

LiDAR (Light Detection and Ranging) systems that are mounted on drones have revolutionized 3D mapping in agriculture. These systems emit high-frequency laser pulses (up to 1 million points per second) to accurately measure distances and create detailed 3D models. The authors of [35] showed how drone-mounted LiDAR outperformed other acquisition techniques and how it can provide high-resolution 3D maps of agricultural fields with very high vertical accuracy.

Microwave Sensors

Microwave sensors that are mounted on drones offer unique capabilities for assessing soil properties and environmental conditions in agriculture. Operating in the 1–300 GHz range, these sensors can penetrate vegetation canopies to provide insights into underlying soil conditions. The authors of [36] demonstrated the effectiveness of drone-mounted ultra-wideband radar for retrieving snowpack properties, which is crucial for predicting spring soil moisture conditions in snow-affected agricultural regions. This non-invasive technique accurately measures snow depth and density, aiding in water resource management for agriculture. The authors of [37] explored drone-borne ground-penetrating radar (GPR) for digital soil mapping. Their research demonstrated the potential for high-resolution mapping of soil layers and subsurface features without soil disturbance. This advancement offers farmers detailed insights into soil structure and composition, enabling more informed decisions about soil management and crop planning.

Precision Spraying Systems

Drone-mounted precision spraying systems allow for targeted application of pesticides, herbicides, or fertilizers. The authors of [38] detailed recent advancements in drone spraying systems, highlighting their potential to reduce chemical use by 45% compared to traditional methods. Modern spraying drones can cover up to 10 hectares per hour, with tank capacities of 10–20 L and variable-flow nozzles enabling ultra-precise application (down to 1 mL/m^2). Automatic flow control systems, coupled with speed and altitude sensors, ensure uniform application even under variable flight conditions.

Environmental Sensors (Temperature, Humidity, Wind)

Drones equipped with environmental sensors provide valuable data regarding the microclimatic conditions of crops [39]. These sensors are essential for optimizing crop management and preventing diseases.

Seeding and Planting Systems

Drones for seeding and planting represent a major innovation in precision agriculture. These drones often use pneumatic projection systems capable of propelling seeds or planting capsules at speeds of 200–300 km/h, allowing effective penetration into the soil even on difficult terrain. The authors of [40] explored the use of drones for assisted pollination, demonstrating their potential to improve yields in fruit crops.

The following table summarizes specialized sensors and payloads that are used in agricultural drones, highlighting their types and applications within the field (Table 2).

Table 2. Specialized sensors and payloads for agricultural drones: types and applications.

Sensor Type	Description	Specific Applications in Agriculture
RGB	High-resolution cameras capturing natural color images	- General crop mapping - Visual assessment of plant health - Estimation of crop density - Detection of damaged or infested areas

Table 2. *Cont.*

Sensor Type	Description	Specific Applications in Agriculture
Multispectral	Sensors capturing light across multiple specific spectral bands, usually including near-infrared	- Calculation of vegetation indices (e.g., NDVI) - Assessment of plant health and vigor - Early detection of crop stress - Estimation of chlorophyll content
Hyperspectral	Sensors capturing light across hundreds of narrow contiguous spectral bands	- Detailed analysis of plant biochemical composition - Early disease detection - Accurate assessment of nutritional deficiencies - Identification of plant species and weeds
Thermal	Cameras capturing infrared radiation emitted by objects	- Detection of crop water stress - Assessment of irrigation efficiency - Detection of leaks in irrigation systems - Monitoring crop temperature
LiDAR	Systems using lasers to measure distances and create 3D models	- Accurate 3D mapping of crops and terrain - Estimation of biomass and plant structure - Canopy analysis for fruit trees
Microwave Sensors	Sensors operating in the 1–300 GHz range, capable of penetrating vegetation canopies	- Retrieval of snowpack properties - High-resolution soil mapping - Assessment of soil moisture
Radiation Sensors	Measure solar radiation intensity	- Assessment of photosynthetic efficiency in crops - Optimization of solar panel placement on farms
Pollen Sensors	Collecting and analyzing pollen particles in the air	- Monitoring pollen dispersion for sensitive crops - Forecasting pollination periods for beekeeping

3.3. Data Processing and Analysis

3.3.1. Mission Planning and Execution Software

Mission planning software is essential for optimizing drone operations in agriculture. The authors of [31] emphasized the importance of these tools for effective flight planning and trajectory optimization. Examples of software include DJI_GroundStation_Pro [41], which offers advanced mission planning for DJI drones; Pix4Dcapture [42], which enables automated flight planning for mapping and surveying; UgCS (2024) [43] and Dronedeploy [44], which are versatile mission planning software applications that are compatible with various drone models; and Litchi, which provides advanced mission planning features for DJI drones. These software solutions play a crucial role in enhancing the efficiency and precision of agricultural drone operations, allowing farmers and operators to plan and execute complex missions with greater ease and accuracy.

3.3.2. Image and Data Processing Systems

Spectral Analysis Algorithms

Spectral analysis algorithms are crucial for interpreting data collected by multispectral and hyperspectral sensors. The authors of [33] have provided a detailed review of these techniques in their study on hyperspectral imaging in precision agriculture. Examples of software include ENVI [45], which is professional software for analyzing hyperspectral and multispectral images; Pix4Dfields [46], which specializes in agricultural image analysis, including spectral analysis tools; QGIS [47], ArcGIS [48], and Pix4Dfields [46], which offer spectral analysis modules in their image processing packages. These software solutions play a vital role in extracting meaningful information from the complex spectral data that are collected by drones, thereby enabling farmers and researchers to gain valuable insights into crop health, soil conditions, and other critical agricultural parameters.

Multi-Sensor Data Fusion Technique

Data fusion from different sensors allows for a more comprehensive and accurate analysis of crop conditions. These techniques are widely used to combine data from various sensor types [49].

Examples of software include QGIS, which is an open-source software providing tools for geospatial data fusion; Agisoft_Metashape [50], which allows the fusion of data from different sensor types for creating 3D models and orthomosaics; and GlobalMapper [51], which offers advanced data fusion capabilities for geospatial analysis. These software solutions enable researchers and agricultural professionals to integrate data from multiple sources, enhancing the depth and accuracy of their analyses and providing a more holistic view of crop health and field conditions.

Artificial Intelligence and Machine Learning

Artificial intelligence and machine learning play an increasingly important role in analyzing data collected by drones. The authors of [52] provided a systematic review of the use of AI and IoTs in agriculture, highlighting their potential for early disease detection and crop classification. Examples of software and platforms include Tensorflow [53], an open-source library for developing machine learning models; Pytorch [54], a popular deep-learning framework for AI research and development; Ibm_Watson [55], an AI platform offering solutions for agriculture, including crop disease detection; and Microsoft_Azure_AI [56], which provides AI services for agriculture, including crop classification and disease detection. These tools can enable researchers and agricultural professionals to develop and deploy sophisticated algorithms for analyzing drone-collected data, enhancing the accuracy and efficiency of crop monitoring and disease identification.

Machine learning models are increasingly used to predict crop yields from data collected by drones. This application is rapidly growing in the field of precision agriculture. Examples of software include CropSafe [57], which uses AI to predict yields and detect anomalies in crops; Descartes_Labs [58], which is a geospatial analysis platform using AI for agricultural yield forecasting; and OneSoil [59], which combines satellite imagery and AI for yield prediction and crop management. These advanced software solutions leverage the power of artificial intelligence and drone-collected data to provide farmers with accurate yield predictions, which enables better planning and resource allocation throughout the growing season.

Decision-Support Systems for Crop Management

Decision-support systems integrate data that are collected by drones to provide precise recommendations to farmers. These systems optimize agricultural practices based on specific crop conditions and environmental data. Examples of software include Agrivi, which is an agricultural management platform offering recommendations based on collected data; Farmers Edge, which provides decision-support tools based on agricultural data analysis, including drone data; and Taranis, which uses drone imagery and AI to provide crop management recommendations [60].

The integration of advanced technologies, from sophisticated aerial platforms to AI-based data processing systems, highlights the rapid evolution of agricultural drones [61]. This section has focused on the importance of mission planning software, image processing systems, AI applications, and decision-support systems that collectively enhance the efficiency and effectiveness of agricultural practices through precise data collection and analysis (Figure 3).

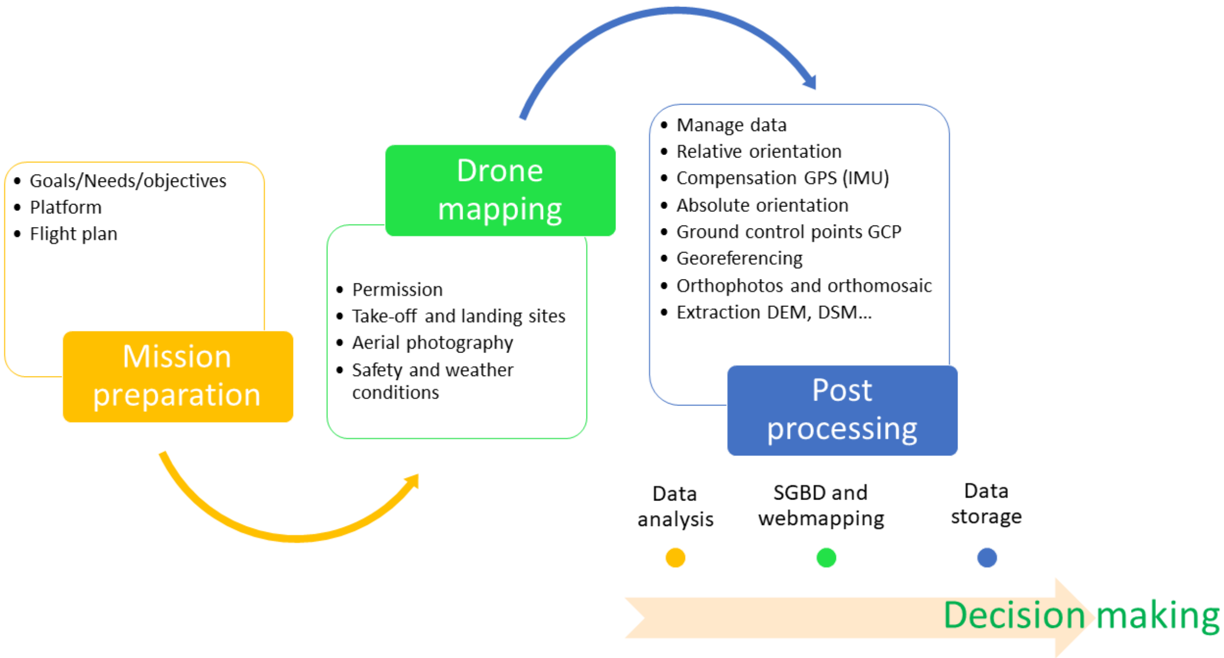

Figure 3. Data workflow in precision agriculture: from drone acquisition to farmer decision support.

3.4. *Quantitative Analysis of Drone Technologies in Precision Agriculture*

This section provides a comprehensive quantitative analysis of drone performance characteristics in precision agriculture applications, drawing from recent studies.

3.4.1. Drone Platform Performance

Table 3 presents a comparative analysis of key parameters for fixed-wing, multi-rotor, and helicopter drones used in agricultural settings, synthesizing data from multiple sources [10,11,21].

Table 3. Comparative analysis of key parameters for fixed-wing, multi-rotor, and helicopter drones.

Parameter	Fixed-Wing Drones	Multi-Rotor Drones	Helicopters
Weight (kg)	5–23	0.25–20	5–35
Flight Time (min)	30–120	15–45	15–45
Maximum Speed (m/s)	15–50	3–20	10–30
Area Covered per Flight (ha)	10–40	1–8	4–12
Payload Capacity (g)	300–1000	300–10,000	300–10,000
Spatial resolution (cm/pixel)	0.6–5	0.6–5	0.6–5

These data highlight the diverse capabilities of different drone types in agricultural applications. Fixed-wing drones excel in area coverage and endurance, making them ideal for large-scale surveys. In contrast, multi-rotors offer greater maneuverability and precision, particularly useful for detailed crop inspections and targeted interventions.

3.4.2. Spatial Resolution and Sensor Capabilities

Drone-based imaging systems have revolutionized agricultural data collection, achieving spatial resolutions ranging from 0.6 cm/pixel to 20 cm/pixel, depending on flight altitude and sensor specifications [31]. This high-resolution imaging capability enables precise crop monitoring and early stress detection, significantly enhancing agricultural management practices [10].

3.4.3. Payload Capacity and Specialized Applications

While most agricultural drones have payload capacities between 300 g and 1000 g, specialized models for applications like crop spraying can support up to 50 kg of liquid products [62]. This expanded capacity has opened new avenues for precision agriculture, allowing for targeted and efficient application of inputs.

3.4.4. Key Equations Governing Sensing Mechanisms

To enhance understanding of drone technologies in precision agriculture, we provide key equations governing various sensing mechanisms:

The Normalized Difference Vegetation Index (NDVI): the NDVI is used to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health. The NDVI is calculated as a ratio between the red (R) and near-infrared (NIR) values:

$$\text{NDVI} = (\text{NIR} - \text{R})/\text{NIR} + \text{R})$$

The Green Normalized Difference Vegetation Index (GNDVI): the GNDVI is the green vegetation index that uses the near infrared (NIR) and green band (Green) of the electromagnetic spectrum:

$$\text{GNDVI} = (\text{NIR} - \text{Green})/(\text{NIR} + \text{Green})$$

The Photochemical Reflectance Index (PRI): the PRI was usually calculated as follows:

$$\text{PRI} = (\text{R}_{531} - \text{R}_{570})/(\text{R}_{531} + \text{R}_{570})$$

where R_{531} and R_{570} are the reflectance at 531 nm and 570 nm, respectively.

The Crop Water Stress Index (CWSI): thehe temperature references (T_{dry} and T_{wet}) are used in conjunction with T_c to obtain the CWSI:

$$\text{CWSI} = (\text{T}_\text{c} - \text{T}_\text{wet})/(\text{T}_\text{dry} - \text{T}_\text{wet})$$

where T_c is the actual canopy temperature obtained from the thermal image and T_{wet} and T_{dry} are the lower and upper boundary temperatures, corresponding to a fully transpiring leaf with open stomata and a non-transpiring leaf with closed stomata, respectively.

3.4.5. Comparison Between Drone-Based Methods and Traditional Manual Practices

Drones are significantly transforming precision agriculture by enhancing efficiency and sustainability in farming practices. They provide numerous advantages over traditional methods, including reduced implementation costs and the ability to execute tasks up to 68 times faster, allowing farmers to cover large areas quickly [21].

With data accuracy reaching up to 90%, drones help surpass the variability associated with manual methods, which often depend on operator skill [31].

Additionally, they decrease labor requirements, alleviating the demand for manual work and lowering associated costs, which is particularly beneficial in an industry facing labor shortages. Drones enable comprehensive information collection on soil and crop conditions, providing detailed data on pH levels, soil types, and chemical content. Their applications include monitoring crop health, targeted pesticide spraying, precise seeding, and efficient water management. This versatility enhances agricultural productivity by facilitating tailored interventions based on real-time data analysis [10].

In summary, drone systems for precision agriculture represent a remarkable convergence of advanced technologies, ranging from sophisticated aerial platforms to artificial intelligence-based data processing systems. This section has highlighted the rapid evolution of agricultural drones, their classification, and the key components that make them so effective in the agricultural context [63]. We have explored in detail the complex architecture of these systems, including aerial platforms, navigation and control systems, communication systems, and ground control stations. The importance of specialized sensors and payloads has been emphasized, showing how these technologies enable precise and diverse data collection on crop conditions and environmental factors. Furthermore, we have examined significant advancements in data processing and analysis, highlighting the crucial role of artificial intelligence and machine learning in interpreting data collected by drones. These technological developments pave the way for more precise, efficient, and sustainable agriculture. Yet, to fully understand the impact of these systems, it is essential to examine their concrete applications in the agricultural field.

In the next section, we will explore in detail the diagnostic applications of drones in agriculture. This part will allow us to see how the previously described technologies are put into practice to monitor crops, assess their health, and provide crucial information to farmers for optimal management of their farms.

4. Diagnostic Applications of Drones in Agriculture

Diagnostic applications of drones in agriculture represent a major advancement in the field of precision agriculture. This section explores how drones are used for crop monitoring, offering powerful tools for plant health assessment, early detection of diseases and pests, as well as water stress analysis. These applications allow farmers to make informed decisions, optimize resource use, and improve crop productivity [64].

4.1. Crop Monitoring

4.1.1. Plant Health Assessment

Plant health assessment using drones has seen significant advancements in recent years, providing farmers with precise and non-invasive diagnostic tools. The authors of [65] provided a comprehensive review of the use of multispectral drone imaging in precision agriculture. Their study highlighted how these sensors can detect non-visible stresses, such as nutritional deficiencies or early pest infestations, long before they become apparent to the naked eye. This early detection allows rapid intervention, thus optimizing input use and reducing costs. The authors of [66] conducted an in-depth study on the use of deep learning for identifying plant and crop diseases from aerial images that are captured by drones. Their review highlights recent advances in the application of artificial intelligence techniques for analyzing drone images in crop health assessment. This innovative approach, combining advanced neural networks with aerial image analysis, demonstrates the considerable potential of AI to improve the accuracy and efficiency of plant disease detection. The authors of [67] demonstrated the effectiveness of drones that were equipped with high-resolution RGB cameras for estimating wheat plant density. Their study revealed a strong correlation (R^2 = 0.91) between drone estimates and ground measurements, thereby providing a valuable tool for cereal crop management.

4.1.2. Early Detection of Diseases and Pests

Early detection of diseases and pests is crucial for preventing significant yield losses. Drones that are equipped with advanced sensors play an increasingly important role in this field. The authors of [32] demonstrated the effectiveness of drone imaging for weed detection in crops. Their study revealed that this technology can accurately distinguish weeds from main crops, even at early growth stages, with an accuracy of up to 93%.

The authors of [52] provided a systematic review of the use of artificial intelligence (AI) and the Internet of Things (IoTs) in agriculture, highlighting the potential of drones integrated into IoTs systems for early disease detection. Their analysis showed that integrating AI into drone image analysis can significantly improve disease detection accuracy compared to traditional methods.

4.1.3. Water Stress Analysis

Recent advances in crop water stress detection illustrate the growing importance of remote sensing technologies in precision agriculture. The authors of [68] developed a low-cost device based on thermal infrared sensors to measure canopy temperature in olive trees (*Olea europaea* L.) and monitor their water status. This innovation offers an accessible alternative to farmers for more precise irrigation management. In parallel, the authors of [34] explored the use of multispectral images that are acquired by drones to diagnose water stress in winter wheat. Their study combined image texture analysis with vegetation indices, demonstrating a significant improvement in water stress detection accuracy compared to traditional methods. These two studies underscore the importance of integrating various sensor technologies and image analysis for more accurate and early assessment of crop water stress, paving the way for more efficient irrigation strategies and better water resource management in agriculture.

4.2. Mapping and Imaging

4.2.1. Two-Dimensional and Three-Dimensional Field Mapping

Drone mapping offers unprecedented precision and resolution for crop management. The authors of [30] conducted a comprehensive review of drone applications in agriculture, highlighting their ability to produce maps with spatial resolution up to 0.5 cm/pixel. This high resolution allows for a detailed analysis of intra-field variability, which is crucial for differentiated crop management. The authors of [69] explored the use of drones that were equipped with multispectral sensors for individual vine analysis in a multi-temporal context. Their study used RGB and multispectral images to assess spatial and temporal variability in vineyards. Their results showed that this approach enables detailed analysis of individual vine health and vigor, with potential applications for differentiated vineyard management and optimization of viticultural practices. Furthermore, the authors of [31] demonstrated the effectiveness of drones in mapping Posidonia (Neptune seagrass) debris and marine waste in coastal ecosystems. This innovative application underscores the versatility of drones for environmental mapping beyond purely agricultural applications, opening new perspectives for integrated coastal and agricultural zone management. These advancements in drone mapping open new perspectives for more precise and sustainable management of crops and ecosystems, allowing farmers and environmental managers to optimize resource use and improve decision-making based on accurate and up-to-date data.

4.2.2. Multispectral and Thermal Imaging

Multispectral and thermal imaging by drone offers unique insights into crop health and environmental conditions. These technologies enable early and precise detection of plant stress, nutritional deficiencies, and pest infestations. The authors of [70] developed an innovative approach by combining multispectral drone imaging with machine learning techniques to rapidly predict winter wheat yield and nitrogen use efficiency (NUE). Their method demonstrated remarkable accuracy, offering farmers a powerful tool to optimize crop management and fertilizer use. In the field of thermal imaging, the authors of [71] explored the use of visible and thermal images that were acquired by drones to monitor water status, canopy growth, and yield of olive trees under different irrigation regimes. Their study revealed that thermal drone imaging can effectively detect water stress in olive trees, with a significant correlation between thermal indices and ground physiological measurements. This approach allows for more precise irrigation management, which is adapted to the specific needs of different olive varieties.

The authors of [72] introduced an innovative approach combining multispectral imaging and deep learning for early disease detection in vineyards. Their system demonstrated 96% accuracy in detecting grapevine downy mildew (*Plasmopara viticola*), surpassing traditional methods and offering considerable potential for integrated pest management.

4.3. Soil and Environmental Assessment

The use of drones for soil and environmental assessment represents a significant advancement in precision agriculture. This technology allows for detailed and non-invasive analysis of soil and environmental conditions, providing farmers with crucial information to optimize crop and resource management [73].

4.3.1. Analysis of Soil Quality and Moisture

Accurate assessment of soil quality and moisture is essential for effective crop management. Drones that are equipped with specialized sensors offer new possibilities in this field. The authors of [74] demonstrated the effectiveness of drones that were equipped with hyperspectral sensors for soil moisture assessment. Their study revealed that using machine learning techniques to analyze hyperspectral data allows for high-precision estimation of soil moisture, which provides a powerful tool for irrigation management. The authors of [75] introduced an innovative approach to high-throughput phenotyping of crop water use efficiency using multispectral drone imagery and a daily soil water balance model. Their study demonstrated that this method allows for accurate estimation of crop water use efficiency (WUE). This approach offers a valuable tool for varietal selection and optimization of irrigation practices, enabling farmers and researchers to assess crop water performance rapidly and accurately over large areas. The authors of [6] emphasized the crucial importance of soils in achieving the Sustainable Development Goals (SDGs), with a direct impact on 13 of the 17 goals. Their study reveals that improving soil management could sequester up to 2.6 gigatons of carbon per year (7% of anthropogenic CO_2 emissions) and increase global food production by 58%. Although not specifically addressing drones, this research highlights the importance of employing advanced technologies for precise soil analysis, which is essential for sustainable agriculture and climate change mitigation.

4.3.2. Drainage Mapping

Precise mapping of field drainage is essential for preventing erosion, optimizing water use, and improving crop health. Drones offer new possibilities in this area, allowing for detailed and non-invasive analysis of agricultural drainage systems. The authors of [76] explored the perspectives of drone remote sensing for precision agriculture, including drainage mapping. Their study highlighted how drones can be used to identify areas of poor drainage and optimize irrigation systems. The authors emphasized that drones equipped with multispectral and thermal sensors can detect subtle variations in soil moisture and plant health, indicative of drainage problems. Accurate mapping of underground agricultural drainage systems is crucial for efficient water management and erosion prevention. The authors of [77] explored an innovative approach combining drone imagery and ground-penetrating radar (GPR) to map these systems. Their study demonstrated the effectiveness of this hybrid method. The authors used drones that were equipped with multispectral cameras to identify potential underground drainage areas based on differences in crop growth and soil moisture that were visible on the surface. These aerial data were then combined with GPR measurements on the ground surface for precise localization of drainage pipes. This approach significantly improved the efficiency of mapping underground drainage systems compared to traditional methods. The results showed a drainage pipe localization accuracy of over 90% under various soil and crop conditions. Moreover, this method considerably reduced the time and costs that were associated with mapping drainage systems, thereby offering a valuable tool for agricultural management and maintenance intervention planning.

4.3.3. Weed Detection

Precise weed detection is crucial for effective crop management and optimized herbicide use [78]. Drones that are equipped with advanced sensors offer new possibilities in this field, and image analysis techniques continue to evolve rapidly [79] introduced an innovative approach using Transformer models for weed mapping from drone images. This method demonstrated remarkable accuracy in weed detection and classification, surpassing conventional image processing techniques. The authors reported a significant improvement in detection accuracy compared to methods that were based on convolutional neural networks (CNNs), achieving an overall accuracy of 92% in varied field conditions. The authors of [80] developed an automatic method for weed mapping in fields of oats (*Avena sativa* L.). Their approach uses a combination of RGB and multispectral images to identify and map weeds with high precision. The authors achieved an overall accuracy of 95% in weed classification, demonstrating the effectiveness of their method for targeted herbicide management. These studies highlight the growing importance of advanced artificial intelligence and image processing techniques in interpreting data that are collected by drones. The use of Transformers by the authors of [79] and the automated approach in [80] demonstrate the potential of AI technologies to solve complex problems in agriculture, particularly precise weed detection.

These advancements allow not only for more accurate weed detection but also for better differentiation between species, which is crucial for targeted herbicide management. This increased precision paves the way for more sustainable agricultural practices, enabling a significant reduction in herbicide use while maintaining high efficiency in weed control. The following table summarizes the diagnostic applications of drones in agriculture, detailing their descriptions, recent studies, and key results for each application area (Table 4).

Table 4. Diagnostic applications of drones in agriculture.

Diagnostic Application	Description	Key Results	Recent Studies
Crop Monitoring			
Plant Health Assessment	Use of multispectral sensors to detect non-visible stress	Early detection of nutritional deficiencies and pest infestations; accurate estimation of wheat plant density (R^2 = 0.91)	[32,65–67]
Early Detection of Diseases and Pests	Use of AI and deep learning to analyze drone images	Up to 93% accuracy in weed detection; significant improvement in early disease detection	[77,79,80]
Water Stress Analysis	Use of thermal sensors to measure canopy temperature	Low-cost device to measure water stress; improved accuracy in detecting water stress in winter wheat	[68,81]
Mapping and Imaging			
2D and 3D Field Mapping	Production of high-resolution maps for intra-field variability analysis	Spatial resolution up to 0.5 cm/pixel; accurate assessment of marine debris on coastal ecosystems	[30,69]
Multispectral and Thermal Imaging	Capture and analysis of images in different spectral bands	Rapid yield prediction; Efficient detection of water stress with high accuracy	[77]
Soil and Environmental Assessment			
Soil Quality and Moisture Analysis	Use of hyperspectral sensors to assess soil moisture	Accurate estimation of soil moisture; Tools to optimize irrigation management	[74,75]
Drainage Mapping	Identification of problematic areas in drainage systems	Drainage pipe localization accuracy over 90%; Optimization of irrigation systems	[76,77]
Weed Detection	Use of advanced models to identify weeds	Overall accuracy of 92–95% in detection; Targeted herbicide management	[79,80]

5. Interventional Applications of Drones in Agriculture

Drones are no longer limited to monitoring and diagnostics in agriculture. They now play a crucial role in direct interventions on crops, offering precise and effective solutions for various agricultural operations (Table 5). This section explores the interventional applications of drones, demonstrating their potential to revolutionize traditional agricultural practices [82].

5.1. Precision Spraying

Precision spraying by drones represents a major advancement in the application of agricultural inputs, offering increased precision and efficiency compared to conventional methods [83].

5.1.1. Fertilizer Application

The authors of [84] provided a detailed review of drone applications for fertilizer spraying. Their study highlights that drones offer several advantages over traditional methods, including better application precision and reduced fertilizer usage. The authors report that using drones for fertilizer application can reduce fertilizer consumption by up to 30% while maintaining or improving crop yields. The authors of [85] conducted a comparative study on the use of agricultural drones for monitoring and spraying. Their results show that drones equipped with precision spraying systems can apply liquid fertilizers with 90–95% accuracy, allowing for more uniform and targeted nutrient distribution. This increased precision translates into better nutrient absorption by plants and reduced fertilizer leaching.

5.1.2. Pesticide and Herbicide Spraying

The authors of [86] examined the application of drones for crop health monitoring and pesticide and fertilizer spraying. Their study highlights that drones can significantly reduce pesticide use through more targeted applications. The authors report a reduction in pesticide use of up to 40% compared to conventional spraying methods [84] and also emphasize the effectiveness of drones in spraying pesticides and herbicides. Their review indicates that drones can cover large areas quickly, thereby reducing application time and minimizing worker exposure to chemicals. The authors note that drone spraying can be up to 5 times faster than traditional manual methods. The authors of [85] observed that drones equipped with multispectral sensors can accurately identify weed-infested areas, allowing for targeted herbicide application. This approach can reduce herbicide use by 50 to 80% compared to broad-spectrum spraying methods.

5.2. Drone-Assisted Seeding and Planting

Drones are revolutionizing seeding and planting practices in agriculture, offering unprecedented precision, efficiency, and accessibility, particularly in hard-to-reach areas or for large-scale forest regeneration [87–89].

5.2.1. Technological Innovations

The authors of [90] presented an innovative approach using drone swarms for direct seeding. Their research demonstrates that the coordinated use of multiple drones can significantly increase the efficiency and coverage of aerial seeding. The authors emphasized the importance of seed dispersal technology, particularly the use of special coatings and encapsulations, to improve the germination and survival of drone-dispersed seeds.

5.2.2. Integration of Artificial Intelligence

The authors of [91] presented an innovative approach combining the use of drones and artificial intelligence to optimize the precision seeding process. The authors developed a workflow that uses machine learning algorithms to analyze high-resolution aerial images and environmental data that were collected by drones. This method allows for precise determination of the best locations for seeding, considering multiple factors such as topography, sun exposure, drainage, and potential plant interactions. The approach aims to significantly improve the efficiency of drone seeding by optimizing planting density and adapting seeding parameters to the specific conditions of each field area. By adapting seeding parameters to the specific conditions of each area, this method aims to improve the efficiency of drone seeding, while highlighting the potential of AI to transform agricultural practices towards more sustainable precision agriculture.

5.2.3. Seed Dispersal Mechanisms

The authors of [92] provided an in-depth analysis of the mechanisms of drone seeding technology. Their study explored various aspects of this innovative approach, including different seed distribution systems, such as mechanical and pneumatic methods. The researchers examined the influence of drone speed and flight altitude on seed dispersal, highlighting how these factors can significantly impact the effectiveness of aerial seeding operations. Additionally, they emphasized the importance of considering environmental conditions such as wind and humidity, which play crucial roles in determining seeding efficiency. The study also shed light on recent innovations in biodegradable seed capsules, which are designed to protect seeds upon impact with the ground, thereby enhancing germination rates and overall seeding success. This comprehensive analysis offers valuable insights into optimizing drone-based seeding techniques for various agricultural applications.

5.2.4. Challenges and Perspectives

Despite notable advances in the use of drones for seeding and planting, several challenges remain to be overcome, including improving seed technology, which is essential for increasing plant survival rates, as well as developing appropriate regulations to govern the use of drones in agriculture and forestry [87]. Optimizing drone autonomy is also a crucial issue to allow coverage of larger areas in a single mission. Furthermore, integrating seeding data into existing agricultural and forestry management systems is also necessary to maximize operational efficiency. Yet, the prospects are promising: the development of drones that are capable of planting not only seeds but also trees and shrubs could transform reforestation practices. The integration of fertilization and irrigation systems into seeding drones, together with the increasing use of artificial intelligence to predict and optimize plant survival rates based on local conditions, paves the way for more sustainable and efficient agriculture.

5.3. Drone-Assisted Pollination

Drone-assisted pollination represents a promising innovation in precision agriculture, offering a potential solution to the challenges posed by the decline of natural pollinators [93,94].

5.3.1. Technological Innovations

The authors of [95] developed an innovative method for autonomous navigation of pollination drones. Their system uses advanced computer vision and deep-learning techniques to enable drones to accurately locate and navigate to flowers for pollination. This advancement significantly improves the efficiency and precision of drone-assisted pollination.

5.3.2. Efficiency and Environmental Impact

The authors of [96] emphasized the importance of considering pollination drones as a complement rather than a replacement for natural pollinators. They caution against excessive reliance on technology and stress the importance of maintaining the biodiversity of natural pollinators for ecosystem health.

5.3.3. Practical Applications

The authors of [97] explored an innovative spraying method for artificial pollination of date palms (*Phoenix dactylifera* L.) using drones. Their approach demonstrated a significant improvement in pollination efficiency and cost reduction compared to traditional methods.

The authors of [40] provided a comprehensive analysis of current artificial pollination technologies, including the use of drones. They highlighted the potential benefits of these technologies, such as increased yields and reduced dependence on natural pollinators, while also emphasizing remaining challenges, particularly optimizing precision and adapting to different plant species.

5.4. Beneficial Insect Release

The use of drones for releasing beneficial insects represents a major innovation in the biological control of crop pests and disease vectors. This approach is part of sustainable agriculture and public health efforts, offering precise and ecological solutions [98].

5.4.1. Efficiency and Precision of Releases

The authors of [99] demonstrated the effectiveness of drones for dispersing *Trichogramma* spp., a Hymenopteran egg-parasitoid used against agricultural and forest pests. Their results show that drones can perform uniform and precise distribution of these beneficial insects over large areas, surpassing traditional methods in terms of coverage and efficiency.

5.4.2. Applications in Urban and Rural Settings

The authors of [100] explored the use of drones for releasing sterile mosquitoes (e.g., *Culex* spp., *Aedes* spp., *Anopheles* spp.) in various environments. This study highlights the adaptability of drones to urban and rural contexts while complying with European regulations. Their work demonstrates the potential of drones for targeted interventions in mosquito population control, thus contributing to the fight against vector-borne diseases.

5.4.3. Improvement of Integrated Pest Management

The authors of [101] compiled research demonstrating the versatility of drones in pest insect management. This collection highlights how drones are revolutionizing not only the release of beneficial insects but also pest population monitoring and targeted application of biopesticides, offering a holistic approach to integrated pest management.

5.4.4. Vector-Borne Disease Control

The authors of [102] examined the use of drones for surveillance and control of malaria vectors and other vector-borne diseases. Their research underscores the potential of drones in mapping vector habitats and implementing targeted interventions, opening new perspectives for public health in regions affected by these diseases.

5.4.5. Challenges and Perspectives

Despite promising advances in drone use for biological control, challenges persist, such as optimizing release techniques to ensure beneficial insect survival and effectiveness in varied environments and adapting drones to different insect types and ecological contexts. Additionally, establishing regulations for drone use is crucial, with attention to safety and environmental protection. Current research is focused on improving release precision, developing advanced distribution systems, and integrating real-time monitoring technologies to measure intervention impacts.

Drone applications address significant agricultural challenges, including optimizing resource use, reducing environmental impact, and adapting to climate change. Nevertheless, these technologies are still evolving, requiring further research to optimize their application and assess long-term ecosystem impacts, alongside addressing regulatory, ethical, and safety considerations [103].

Table 5. Interventional applications of drones in agriculture.

Interventional Application	Key Results	Description	Recent Studies
Precision Spraying			
Fertilizer Application	Reduction in fertilizer use; Improved application efficiency	Use of drones for targeted fertilizer application	[84,85]
Pesticide and Herbicide Spraying	Reduction in pesticide use; Improved application precision	Targeted application of phytosanitary products by drone	[84,86]

Table 5. *Cont.*

Interventional Application	Key Results	Description	Recent Studies
Drone-Assisted Seeding and Planting			
Precision Seeding	Improved seeding precision; Potential for ecological restoration	Use of drones for direct seeding in fields	[90,91]
Tree Planting	Increased planting speed; Application in hard-to-reach areas	Use of drones for reforestation and agroforestry	[104]
Drone-Assisted Pollination			
Artificial Pollination	Improved pollination rates; Potential complement to natural pollinators	Use of drones for crop pollination	[95]
Beneficial Insect Release			
Biological Control	Reduction in pesticide use; Improved efficiency of biological control	Use of drones for releasing predatory or parasitic insects	[99]

6. Related Technologies That Support Drone Use

The integration of drones with other cutting-edge technologies opens new perspectives for precision agriculture. This section explores the synergies between drones and other technological innovations, as well as their effects on integrated farm management.

6.1. Geographic Information Systems (GIS)

The integration of drones with GIS represents a major advancement in mapping and spatial analysis of agricultural operations, offering new perspectives for precise resource management. The authors of [30] provided a comprehensive review of drone applications in agriculture and their integration with GIS. Their analysis highlights the crucial importance of this synergy for more precise spatial analysis and better decision-making based on geospatial data. The authors highlighted how drone–GIS integration enables detailed crop mapping, real-time monitoring of field conditions, and optimized planning of agricultural interventions [31], demonstrating the applicability of this integrated technology beyond traditional agriculture. Their study used Unmanned Aerial Vehicles (UAVs) and machine learning techniques combined with GIS to assess Posidonia (Neptune seagrass) debris and marine waste in coastal ecosystems. This innovative application illustrates the versatility of drone–GIS integration for environmental management and ecosystem monitoring. The authors of [105] explored the latest advances in drone–GIS integration for agricultural applications. Their study highlights how this integration significantly improves the accuracy and efficiency of geospatial data collection in agriculture. The authors emphasize the ability of drones to provide very high-resolution data, allowing detailed mapping of agricultural plots with centimeter precision. They also discuss the use of artificial intelligence and machine learning to process and analyze drone-collected data, offering valuable insights for agricultural management. Furthermore, the study underscores the potential of this integrated technology for real-time monitoring of environmental changes, early detection of crop stress, and optimization of agricultural practices. These recent findings demonstrate that the integration of drones with GIS opens new perspectives for more efficient and sustainable precision agriculture. This approach not only allows for detailed and accurate mapping of agricultural operations but also enables in-depth analysis of spatial data for optimized management of crops and natural resources.

6.2. Internet of Things (IoTs)

The integration of drones with the Internet of Things (IoTs) and Artificial Intelligence (AI) creates a rich and dynamic data system, propelling precision agriculture to new heights of efficiency and responsiveness [106], developing an innovative system for early detection of rice diseases and position mapping using drones and IoTs architecture. Their study, which was presented at the 12th SEATUC conference, demonstrates how the integration of drones with IoTs can substantially improve early disease detection in Asian rice fields (*Oryza sativa* L.), allowing for rapid and targeted intervention. This system combines ground sensors with drones equipped with multispectral cameras, offering a comprehensive solution for rice crop monitoring. The authors of [107] explored the use of IoTs-based drones to improve crop quality in agricultural fields. Their research highlights how these systems can collect real-time data on various crop parameters, allowing farmers to optimize their practices and improve overall production quality. The authors emphasize the importance of integrating IoTs sensors with drones for continuous and accurate monitoring of growth conditions. The authors of [52,108], in their systematic literature review on the application of AI and IoTs in agriculture, highlighted the transformative potential of these technologies. Their analysis emphasizes how the integration of drones into IoTs systems enables large-scale real-time data collection, creating a solid foundation for more precise and timely agricultural decisions. The authors also identify challenges and opportunities that are related to the adoption of these technologies in different agricultural contexts. The authors of [109] provided an in-depth review of the use of AI in agriculture, highlighting its crucial role in interpreting data that are collected by drones. Their study reveals that machine learning algorithms, particularly deep neural networks, excel in the early detection of plant diseases and yield estimation. The authors emphasize the importance of AI in transforming raw data that are collected by drones into actionable information for farmers.

These advancements demonstrate the transformative potential of drones and associated technologies to address major challenges in food security, resource management, and environmental protection in the context of climate change. Despite these significant advances, the widespread adoption and optimization of these technologies face numerous challenges. The next chapter will examine these challenges as well as the prospects for the use of drones in agriculture. We will explore the technical, regulatory, and socio-economic obstacles that must be overcome, together with emerging opportunities that could shape the future of precision agriculture (Table 6).

Table 6. Combined and advanced applications of drones in agriculture.

Application	Description	Key Results	Recent Studies
Integration with Geographic Information Systems (GIS)	Combination of drone data with GIS for advanced spatial analysis	- Detailed mapping with centimeter precision - Assessment of marine debris in coastal ecosystems	[105]
Integration of Internet of Things (IoTs) and Artificial Intelligence (AI)	Use of IoTs and AI to analyze data collected by drones	- Early detection of rice diseases - Improvement of crop quality - Targeted pest management	[106]
Harvest Planning	Optimization of planning based on data collected by drones	- Comparative analysis of drone use in different countries	[110]

7. Challenges and Perspectives

The integration of drones in precision agriculture presents significant opportunities, but it also faces complex challenges that require particular attention from researchers, industry professionals, and policymakers. This section examines the main obstacles to the widespread adoption of drones in agriculture and explores the perspectives of this technology.

7.1. Regulations and Ethical Considerations

7.1.1. Evolution of the Regulatory Framework

The regulatory landscape surrounding the use of drones in agriculture is continuously evolving, with significant variations across different countries. The authors of [110] conducted a comparative analysis of drone use in agriculture, highlighting the regulatory disparities that persist. Their study underscores the need for international harmonization of regulations to facilitate the widespread adoption of drones in agriculture. A major challenge concerns Beyond Visual Line of Sight (BVLOS) operations, which are crucial for monitoring large agricultural areas. Current regulations in many countries limit these operations, thus hindering the full potential of drones in agriculture. For instance:

United States: The Federal Aviation Administration (FAA) mandates that operators obtain special waivers for BVLOS operations, which can be a barrier for small-scale farmers who may lack the resources to navigate complex regulatory processes.

European Union: The European Union Aviation Safety Agency (EASA) has implemented a comprehensive regulatory framework that categorizes drone operations, including BVLOS. Operators must comply with stringent safety and operational requirements to obtain permission, which can be challenging for new entrants in the agricultural sector.

Australia: In Australia, the Civil Aviation Safety Authority (CASA) allows BVLOS operations under specific conditions but requires operators to hold a Remote Pilot License (RePL) and submit an approved safety case.

The authors of [111] also emphasize that regulatory bodies have foreseen challenges when UAS are allowed to perform autonomous missions BVLOS. They detail how EASA regulations require direct connection to and from the remote pilot, segmenting operations according to risk:

Open Operations: These do not require authorization from an aviation authority but must adhere to defined boundaries (e.g., distance from aerodromes and people). UAS must be flown:

Under a direct visual line of sight (VLOS) within 500 m.

At altitudes not exceeding 150 m above ground or water.

Outside specified reserved areas (e.g., airports, environmental zones).

Avoiding flight over crowds, which is prohibited.

Specific Operations: These require a risk assessment leading to an "Operations Authorization" with specific limitations tailored to the operation.

These examples illustrate how varying regulations can impact the ability of farmers to utilize drone technology effectively, particularly in regions where regulatory frameworks are more restrictive.

7.1.2. Ethical and Privacy Considerations

In addition to regulatory challenges, ethical considerations regarding drone use in agriculture are paramount. The authors of [112] conducted a systematic review of ethical implications related to drone usage in environmental and health research, raising critical questions about privacy protection, informed consent, and potential impacts on local ecosystems. In agriculture, these ethical considerations are particularly relevant concerning data collection practices. Farmers must ensure that their use of drone technology respects privacy rights and does not infringe upon the rights of neighboring landowners or communities. Transparency in data collection methods is essential to build trust among stakeholders. The integration of drone technology must also consider potential environmental impacts, such as disturbances to wildlife or alterations to local ecosystems caused by frequent aerial surveillance. Addressing these ethical concerns will be crucial for fostering acceptance and promoting the responsible use of drones within agricultural practices.

7.2. Training and Adoption by Farmers

7.2.1. Barriers to Adoption

The authors of [113] identified key obstacles to drone adoption by small-scale farmers in India. The study highlights three main challenges: lack of technological infrastructure in rural areas; high initial costs of drone acquisition and maintenance; and insufficient technical skills among farmers. These barriers are particularly significant in developing countries, emphasizing the need for tailored approaches to promoting drone adoption. The findings stress the importance of addressing technological, socio-economic, and educational barriers to facilitate drone integration in small-scale farming.

7.2.2. Training and Awareness Strategies

The authors of [114] explored the required skills and training needs of civil drone pilots. Their study emphasizes the importance of training adapted not only to the technical aspects of piloting but also to ethical and regulatory considerations. In the agricultural context, this implies developing specific training programs that consider the unique needs of farmers and local conditions.

7.3. Current Technological Limitations

7.3.1. Autonomy and Payload Capacity

The limited autonomy of drones and their restricted payload capacities remain major challenges for their large-scale use in agriculture. The authors of [110] highlighted the technological differences between countries in terms of agricultural drone capabilities, revealing a growing technological gap.

7.3.2. Sensor Precision and Reliability

The precision and reliability of sensors, particularly in challenging environmental conditions, remain crucial issues. The authors of [113] noted that the reliability of data collected by drones in various climatic conditions is a major concern for farmers, highlighting the need to develop more robust sensors that are adapted to local conditions.

7.4. Future Innovations and Promising Research Areas

7.4.1. Artificial Intelligence and IOTS

The integration of AI and machine learning with data that are collected by drones opens new perspectives for predictive analysis in agriculture. Future research is needed to develop more accurate algorithms adaptable to various agricultural conditions.

7.4.2. Drone Swarms

The use of drone swarms represents a promising frontier for precision agriculture. This approach could allow more efficient monitoring of large agricultural areas and synchronized data collection. However, significant technical challenges remain, particularly in terms of coordination and communication between drones [115].

7.4.3. Harvesting Drones

The development of drones that are capable of harvesting crops represents an exciting frontier in agricultural automation. These specialized drones could potentially reduce labor costs and increase efficiency, particularly for high-value crops or in areas where manual labor is scarce. Research is ongoing to develop drones with the precision and dexterity that are required for various harvesting tasks, from fruit picking to grain collection. However, challenges remain in terms of payload capacity, battery life, and the ability to handle delicate produce without causing damage [116,117].

7.4.4. Drones for Vertical and Controlled Environment Agriculture

Specialized micro-drones are being developed for monitoring and managing crops in vertical farms and greenhouses. These miniature drones, which are equipped with precision sensors, navigate confined spaces to perform tasks such as plant-growth monitoring, early disease detection, and targeted treatment application. This approach could revolutionize crop management in controlled environments by enabling continuous, non-invasive monitoring and rapid response to problems. It also has the potential to reduce human intervention, improving efficiency and reducing contamination risks. Although still in development, this innovation represents a promising direction for integrating drone technologies into advanced agricultural systems, particularly in urban contexts where sustainable food production in limited spaces is crucial.

In summary, while the challenges are numerous, the prospects for the use of drones in agriculture are extremely promising. The evolution of regulations, improved farmer training, technological advancements, and integration with other agricultural innovations pave the way for more precise, efficient, and sustainable agriculture (Table 7). The key to success will lie in the ability to overcome these challenges collaboratively, considering local specificities and ensuring ethical and responsible adoption of these technologies.

Table 7. Challenges and perspectives of drone use in agriculture.

Category	Challenges	Perspectives
Reglementary	- Regulatory disparities between countries - Restrictions on operations beyond the-line-of-sight (BVLOS) - Security and confidentiality standards to be established	- International harmonization of regulations - Development of specific regulatory frameworks for agriculture - Gradual easing of BVLOS restrictions
Technologies	- Limited drone autonomy - Sensor accuracy and reliability under a wide range of environmental conditions - Capacity to process large quantities of data	- Improving drone energy efficiency - Development of more robust and precise sensors - AI integration for data processing and analysis
Adoption	- High initial cost for small farms - Lack of technological infrastructure in rural areas - Resistance to change and lack of technical skills among farmers	- Lower costs thanks to economies of scale - Development of specific training programs - Raising awareness of economic and environmental benefits
Ethical and social	- Privacy issues and informed consent for data collection - Potential impact on traditional agricultural employment - Social acceptance of drones in rural areas	- Development of ethical protocols for data collection and use - Training and retraining of farm workers - Awareness campaigns on the benefits of drones in agriculture

8. Conclusions

This comprehensive literature review has illuminated the transformative role of drones in modern agriculture. As an innovative tool, drones offer promising solutions to enhance the efficiency, sustainability, and resilience of agricultural systems in the face of contemporary challenges such as food security and climate change.

The rapid evolution of drones, encompassing enhanced sensors, increased autonomy, and seamless integration with artificial intelligence (AI) and the Internet of Things (IoTs), is paving the way for groundbreaking applications in precision agriculture. These innovations enable more refined management of agricultural resources, optimizing productivity while simultaneously reducing environmental impacts. The ability of drones to provide real-time, high-resolution data on crop health, soil conditions, and resource utilization empowers farmers to make informed decisions, leading to more sustainable and efficient farming practices.

Yet, the widespread adoption of drones in agriculture faces several significant challenges. Regulatory disparities between countries, as well as ethical considerations related to data collection and usage, require careful attention and harmonization efforts. The need for clear, consistent international guidelines on drone usage in agriculture is paramount in facilitating global adoption and ensuring responsible use of this technology. Overcoming barriers that are related to technological accessibility and farmer training is also essential to ensure that these tools are used effectively and responsibly across diverse agricultural settings.

The economic implications of drone adoption in agriculture are substantial. While initial investment costs may be high, the potential for increased yields, reduced input costs, and improved resource management offer significant long-term economic benefits. Future research should focus on quantifying these economic impacts across different scales of agricultural operations and in various global contexts.

The environmental benefits of drone technology in agriculture are particularly noteworthy. By enabling precise applications of inputs such as water, fertilizers, and pesticides, drones can significantly reduce the environmental footprint of agricultural practices. This aligns well with global sustainability goals and the urgent need to mitigate the impacts of climate change on food production systems.

Looking ahead, the prospects for drone use in agriculture are exceptionally promising. The emergence of drone swarms for integrated farm management and the development of environmental DNA sampling drones illustrate the potential for continuous innovation in this field. These advancements could further enhance farmers' abilities to monitor and manage their resources sustainably. The integration of drones with other emerging technologies, such as blockchains for supply chain transparency or advanced AI for predictive modeling, could revolutionize agricultural practices even further.

In conclusion, drones are being positioned as indispensable tools for addressing the agricultural challenges of the 21st century. Their capacity to provide precise data, optimize resource use, and improve productivity while contributing to environmental sustainability paves the way for a sustainable agricultural revolution. Realizing this potential will require close collaboration among researchers, industry professionals, policymakers, and farmers to overcome the identified challenges while ensuring ethical and responsible adoption of these technologies.

As we move forward, it is crucial to maintain a balanced approach that considers both the technological possibilities and the socio-economic realities of diverse agricultural communities worldwide. By doing so, we can harness the full potential of drone technology to create a more resilient, sustainable, and productive global agricultural system capable of meeting the food security needs of a growing world population in the face of climate change and resource constraints.

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