



Drone-Based Precision Agriculture Enhancing Crop Monitoring and Management

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Abstract

Precision agriculture has revolutionized modern farming by introducing data-driven methods that optimize resource use and improve crop yields. Among the various technologies employed, drones have emerged as powerful tools for enhancing crop monitoring and management. This research paper explores the pivotal role of drones in precision agriculture, highlighting their ability to provide high-resolution, real-time data that enables farmers to make informed decisions. The study discusses how drones contribute to more efficient crop monitoring, allowing for early detection of issues such as nutrient deficiencies, pest infestations, and water stress. Additionally, it examines the active role drones play in crop management through targeted applications of fertilizers, pesticides, and irrigation. The integration of drones into precision agriculture not only enhances the accuracy and timeliness of interventions but also promotes sustainable farming practices by reducing resource wastage and minimizing environmental impact. The findings underscore the importance of drones in achieving higher crop yields, lower costs, and a more sustainable agricultural system.

Keywords: Precision Agriculture, Drones, Crop Monitoring, Crop Management, Sustainable Farming, Data-Driven Agriculture, UAVs, Precision Farming.

Introduction

Precision agriculture is revolutionizing the farming industry by introducing advanced technologies that allow for more efficient and sustainable crop management. Unlike traditional agricultural practices, which often involve applying uniform treatments across entire fields, precision agriculture focuses on managing fields with a high degree of specificity. This approach optimizes inputs such as water, fertilizers, and pesticides, leading to improved crop yields, reduced costs, and minimal environmental impact. But how does this system truly differ from traditional methods? Why has it become a focal point in modern farming?

The core of precision agriculture lies in its data-driven approach. Technologies like GPS, remote sensing, and soil sampling are used to gather detailed information about field conditions. This data is then analyzed to guide farming decisions. For instance, by mapping variations in soil fertility within a single field, farmers can apply fertilizers more precisely, targeting only the areas that need them most. Similarly, water usage can be optimized by identifying zones within a field that require different irrigation levels. However, for precision agriculture to be truly effective, continuous and accurate monitoring of crops is essential. This is where drones come into play. Drones, also known as unmanned aerial vehicles (UAVs), have emerged as a powerful tool in precision agriculture, offering a level of flexibility and precision that surpasses traditional methods. They provide farmers with real-time data on crop health, soil conditions, and even pest activity, allowing for timely interventions that can significantly enhance productivity. But why drones? What makes them so suited to the demands of modern farming? According to research, the use of drones in agriculture has proven to be a game-changer, enabling farmers to monitor large areas quickly and accurately. These small, unmanned aircraft can cover vast fields in a fraction of the time it would take for manual inspections, capturing high-resolution images that reveal detailed information about crop conditions. This capability is especially valuable in large-scale farming operations, where the timely detection of issues can make the difference between a good harvest and a poor one [1].

1.2 Role of Drones in Agriculture

Drones have swiftly become essential tools in modern agriculture, particularly within the framework of precision agriculture. These small, unmanned aerial vehicles (UAVs) offer a host of capabilities that align perfectly with the needs of today's farmers. But what exactly makes drones so effective in agricultural applications? How are they reshaping the landscape of farming? One of the primary advantages of drones in agriculture is their ability to cover large areas of land quickly and efficiently. Traditional methods of crop monitoring, such as manual inspections or even satellite imagery, can be time-consuming and often lack the necessary detail. Drones, on the other hand, can fly over vast fields and capture high-resolution images in a fraction of the time. These images provide detailed insights into crop health, soil conditions, and even pest infestations, all of which are crucial for making informed decisions [1].

Equipped with advanced sensors, drones can capture a wide range of data that is invaluable for precision agriculture. For instance, multispectral cameras can detect variations in crop health that are invisible to the naked eye. This allows farmers to identify stressed areas of a field and address issues such as nutrient deficiencies, disease, or water stress before they become severe. Thermal cameras, on the other hand, can be used to monitor water usage and detect areas that are either over- or under-irrigated. This data-driven approach to farming leads to more precise applications of water, fertilizers, and pesticides, ultimately increasing efficiency and reducing costs [2]. Moreover, drones are not limited to passive monitoring; they also play an active role in crop management. For example, drones can be equipped with sprayers to apply fertilizers, pesticides, or herbicides directly to the crops. This targeted application minimizes the amount of chemicals used, reducing both cost and environmental impact. In fact, research has shown that drone-based spraying systems can be up to five times more efficient than traditional methods, allowing for precise application even in hard-to-reach areas [3].

The flexibility of drones also makes them ideal for use in various terrains and crop types. Whether it's a vineyard in a hilly region or a large, flat wheat field, drones can be programmed to fly specific routes, ensuring comprehensive coverage. This adaptability, combined with their ability to provide real-time data, makes drones a vital tool in modern agriculture. But how does this technology translate into tangible benefits for farmers? The integration of drones into precision agriculture allows for more timely and accurate decision-making, leading to higher yields, lower costs, and more sustainable farming practices. According to a study by Mulla (2013), the use of drones in agriculture has the potential to reduce input costs by up to 20% while increasing crop yields by as much as 15% [4]. These figures highlight the significant impact that drones can have on farming profitability and sustainability.

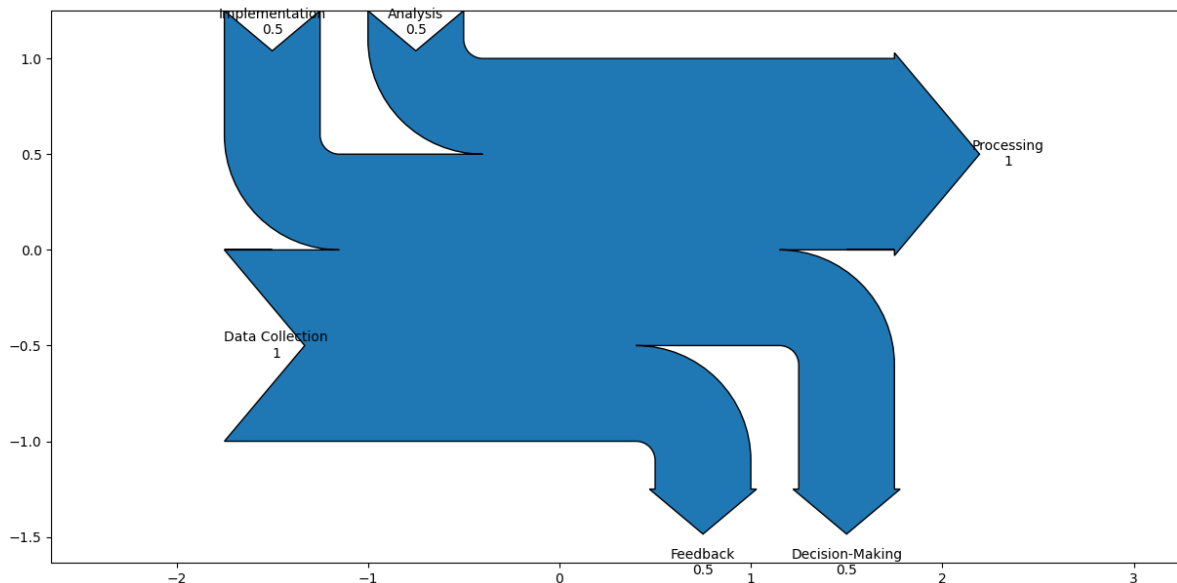


Figure 1 Drone-Based Precision Agriculture Workflow.

1.3 Importance of Crop Monitoring and Management

Crop monitoring involves the continuous observation and analysis of crops throughout their growth cycle. This process allows farmers to detect issues such as nutrient deficiencies, pest infestations, and water stress early on, enabling them to take corrective action before these problems can cause significant damage. Traditional methods

of crop monitoring, which rely on manual inspections and satellite imagery, often fall short in providing the detailed, real-time data necessary for precise interventions. Drones, however, have changed the game by offering a more effective and efficient means of monitoring crops.

The ability of drones to capture high-resolution images and collect data from multiple sensors provides farmers with an unprecedented level of insight into the health and development of their crops. For instance, by analyzing multispectral images captured by drones, farmers can assess the vigor of their crops, identify areas of stress, and determine the exact cause, whether it's a lack of nutrients, insufficient water, or the presence of pests [1]. This detailed information is critical for making informed decisions that can optimize crop health and maximize yields. Moreover, effective crop management is not just about identifying problems—it's about responding to them in a timely and precise manner. This is where drones truly shine. Once issues are detected through monitoring, drones can be deployed to apply treatments such as fertilizers or pesticides directly to the affected areas. This targeted approach ensures that resources are used efficiently, reducing waste and minimizing the environmental impact of farming operations [4]. For example, if a drone detects a pest infestation in a specific area of a field, it can immediately apply pesticide to that area without the need to treat the entire field, saving time, money, and resources. But the benefits of drones in crop management extend beyond just problem-solving. Drones also play a key role in optimizing various farming practices. For instance, by using thermal imaging, drones can monitor soil moisture levels and help farmers manage irrigation more effectively. This ensures that water is used efficiently, reducing waste and preventing issues such as waterlogging or drought stress. In addition, drones can assist in the planning and execution of harvesting operations by providing data on crop maturity, allowing farmers to determine the optimal time for harvest and ensuring that crops are collected at their peak quality.

The importance of crop monitoring and management in precision agriculture cannot be overstated. These practices are essential for maximizing crop yields, reducing input costs, and promoting sustainable farming practices. By leveraging the capabilities of drones, farmers can monitor their crops with greater accuracy and respond to issues more quickly, leading to better outcomes and a more profitable farming operation. According to research by Ballesteros et al. (2015), the use of drones in crop monitoring can improve yield prediction accuracy by up to 30%, highlighting the significant impact that this technology can have on farming success [2].

Technological Foundations of Drone-Based Precision Agriculture

Drones, or unmanned aerial vehicles (UAVs), have become integral to precision agriculture, offering a variety of functions that enhance crop monitoring and management. Different types of drones are employed in agriculture, each designed to meet specific needs based on their capabilities, payload capacities, and the nature of the tasks they are intended to perform. Understanding the types of drones used in agriculture is crucial for selecting the right technology for specific farming applications.

Fixed-Wing Drones

Fixed-wing drones are engineered to mimic the flight dynamics of airplanes, using a rigid wing structure that generates lift as the drone moves forward. This design allows fixed-wing drones to cover large agricultural areas efficiently, making them ideal for extensive mapping and monitoring tasks. They can stay airborne for extended periods, with some models capable of flying for several hours without needing to land, thereby maximizing the area covered in a single flight. The efficiency of fixed-wing drones makes them particularly suited for surveying large-scale farms and plantations, where rapid data collection is crucial. These drones are typically equipped with high-resolution cameras and various sensors, such as multispectral and thermal sensors, which are used to capture detailed images and data across vast expanses of farmland. This data is invaluable for creating detailed maps of crop health, soil moisture levels, and other critical parameters that influence farm management decisions [5]. However, the fixed-wing design also has limitations. These drones require runways or catapult systems for takeoff and landing, which can be a challenge in regions with limited open space. Additionally, their inability to hover in place makes them less effective for close-up inspections or applications that require stationary flight, such as spot spraying of fertilizers or pesticides.

Multi-Rotor Drones

Multi-rotor drones are the most versatile and commonly used type in agriculture. These drones typically have four (quadcopter), six (hexacopter), or eight (octocopter) rotors, which provide lift and stability. The defining feature of multi-rotor drones is their ability to hover in place, offering precise control over movement and positioning. This makes them ideal for detailed, localized tasks, such as close-up inspections, targeted spraying, and real-time monitoring of specific areas. The versatility of multi-rotor drones extends to their payload capabilities. They can be equipped with a variety of sensors and cameras, including high-resolution RGB cameras, multispectral sensors for vegetation analysis, and thermal cameras for detecting plant stress or soil

moisture variations. This allows farmers to gather detailed data on crop health, detect early signs of disease or nutrient deficiencies, and make informed decisions on interventions [6]. Despite their advantages, multi-rotor drones have shorter flight times compared to fixed-wing drones, typically ranging from 20 to 60 minutes. This limitation is due to the high energy consumption required to maintain hovering flight. As a result, multi-rotor drones are generally used for smaller fields or for tasks that require high precision but do not necessitate covering large areas in one flight.

Hybrid Drones

Hybrid drones combine the best features of fixed-wing and multi-rotor designs, offering a versatile solution that can adapt to different agricultural needs. These drones are equipped with rotors for vertical takeoff and landing (VTOL), like multi-rotor drones, but also have fixed wings that allow them to transition to more efficient horizontal flight. This dual capability enables hybrid drones to cover large areas like fixed-wing drones while retaining the ability to hover for detailed inspections. The flexibility of hybrid drones makes them ideal for use in varied terrain where the benefits of both VTOL and fixed-wing flight are needed. For example, they can be used to survey a large agricultural field, map out areas of interest, and then switch to hover mode to conduct a closer inspection of specific spots. This adaptability is particularly useful in precision agriculture, where different types of data collection are often required within the same flight mission [7]. Hybrid drones are relatively new in the agricultural sector, but their potential is significant. They offer longer flight times and greater range than multi-rotor drones, without sacrificing the ability to perform detailed, localized tasks. This makes them a promising option for farmers who need a single drone that can handle a wide variety of tasks, from broad-area monitoring to precise interventions.

Single-Rotor Helicopter Drones

Single-rotor helicopter drones are more powerful and capable of carrying heavier payloads than multi-rotor drones. Their design, which features a single large rotor similar to that of a traditional helicopter, allows them to stay airborne longer and perform tasks that require more substantial equipment, such as LiDAR systems for topographic mapping or larger, more complex cameras for high-resolution imaging. These drones are particularly useful for agricultural tasks that involve carrying heavier payloads, such as spraying applications. For instance, single-rotor drones can be equipped with larger tanks for fertilizers or pesticides, allowing them to cover more ground in a single flight. This makes them ideal for large-scale spraying operations, especially in crops that require frequent treatment or where large quantities of liquid need to be applied [8]. However, the complexity of operating and maintaining single-rotor drones is higher than that of multi-rotor or fixed-wing drones. The larger rotor blade also poses safety risks, particularly during takeoff and landing. As a result, these drones are typically used by more experienced operators or in situations where their specific advantages outweigh the operational challenges.

Autonomous Drones

Autonomous drones represent the forefront of drone technology in agriculture. These drones are equipped with advanced artificial intelligence (AI) systems that enable them to operate independently, without the need for direct human control. Autonomous drones can be programmed to perform specific tasks, follow predetermined flight paths, and make real-time decisions based on the data they collect. The primary advantage of autonomous drones is their ability to conduct continuous, automated monitoring of crops. For example, they can be deployed to fly over a farm at regular intervals, capturing data on crop health, soil conditions, and other critical parameters. This data is then processed and analyzed by onboard AI systems, which can provide farmers with actionable insights and recommendations. Autonomous drones can also be integrated with other smart farming technologies, such as automated irrigation systems or precision sprayers, to create a fully automated, data-driven farming ecosystem [9]. The use of autonomous drones in agriculture is still in its early stages, but the potential benefits are vast. By reducing the need for manual intervention, these drones can increase the efficiency and precision of farming operations, leading to better crop yields and more sustainable practices. As AI and drone technology continue to advance, the role of autonomous drones in agriculture is expected to grow significantly.

Table 1 Types of Drones Used in Agriculture.

Drone Type	Key Features	Common Applications
Fixed-Wing Drones	Long flight time, large area coverage	Large-scale mapping, surveying
Rotary-Wing Drones	Hover capability, high maneuverability	Precision spraying, close-range monitoring
Hybrid Drones	Combination of fixed-wing and rotary-wing benefits	Extended flight time, versatility in applications

Sensors and Imaging Technology

The effectiveness of drones in precision agriculture is largely driven by the advanced sensors and imaging technologies they carry. These components are the eyes and ears of the drones, enabling them to collect detailed data on crop health, soil conditions, and other critical agricultural parameters. Understanding the different types of sensors and imaging technologies used in drone-based precision agriculture is essential for leveraging the full potential of this technology.

- *RGB Cameras*

RGB (Red, Green, Blue) cameras are the most common type of imaging technology used in drones. These cameras capture images in the visible spectrum, much like a standard digital camera. The images obtained from RGB cameras can be used to assess the general health of crops, detect obvious signs of stress, and create maps of the farm for further analysis. One of the main applications of RGB cameras in agriculture is the generation of orthomosaic maps. These are highly accurate, georeferenced maps created by stitching together multiple aerial images taken by the drone. Orthomosaic maps provide farmers with a comprehensive view of their fields, allowing them to identify areas that require attention, such as regions with poor growth or those affected by pests. Additionally, RGB cameras are often used in conjunction with other sensors to provide a more holistic view of the field [10].

- *Multispectral Sensors*

Multispectral sensors are a step beyond RGB cameras, capable of capturing data across multiple wavelengths of light, including those beyond the visible spectrum. These sensors typically capture data in the red, green, blue, near-infrared (NIR), and sometimes even the red-edge spectrum. The ability to detect near-infrared light is particularly valuable in agriculture, as it provides insights into plant health that are not visible to the naked eye.

Multispectral imagery is used to calculate various vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). NDVI is a key indicator of plant health, measuring the difference between the red and near-infrared reflectance of vegetation. Healthy plants reflect more near-infrared light and less visible light, resulting in higher NDVI values. By analyzing these indices, farmers can detect areas of their fields that are under stress due to factors such as water deficiency, nutrient shortages, or disease, long before these issues become visible [11].

- *Thermal Cameras*

Thermal cameras measure the infrared radiation emitted by objects, which is directly related to their temperature. In agriculture, thermal imaging is used to monitor the temperature of crops and soil, providing critical information about water stress, soil moisture levels, and the overall health of the plants. One of the primary applications of thermal imaging in agriculture is irrigation management. By detecting temperature differences in the soil and plant canopy, thermal cameras can identify areas that are experiencing water stress. This information allows farmers to optimize their irrigation practices, ensuring that water is applied precisely where it is needed, reducing waste, and promoting sustainable water use. Additionally, thermal imaging can be used to detect pest infestations and plant diseases, as infected plants often exhibit abnormal temperature patterns [12].

- *LiDAR (Light Detection and Ranging) Sensors*

LiDAR sensors use laser pulses to measure distances and create detailed 3D maps of the terrain and vegetation. In agriculture, LiDAR is used for topographic mapping, which is essential for understanding the landscape and planning agricultural activities. LiDAR can provide high-resolution elevation data, helping farmers with tasks such as drainage planning, soil erosion assessment, and the creation of precise planting patterns. LiDAR's ability to penetrate vegetation also makes it useful for creating digital elevation models (DEMs) and digital surface models (DSMs) that reveal the underlying terrain. These models are critical for precision farming, as they help in identifying areas that are prone to flooding or erosion and assist in the design of effective irrigation systems. Moreover, LiDAR data can be used to assess the biomass of crops, which is an important factor in determining crop yield and planning harvests [13].

- *Hyperspectral Sensors*

Hyperspectral sensors capture data across a much broader range of wavelengths than multispectral sensors, often encompassing hundreds of narrow bands across the electromagnetic spectrum. This technology provides a more detailed spectral signature of crops, enabling the detection of subtle differences in plant health, soil composition, and other critical factors. Hyperspectral imaging is particularly valuable for identifying specific crop diseases, nutrient deficiencies, and even soil contamination. The detailed spectral information provided by hyperspectral sensors allows for the identification of issues at a molecular level, which can lead to early intervention and more precise application of inputs such as fertilizers and pesticides. Although hyperspectral sensors are more

expensive and complex than other types of sensors, their ability to provide detailed, actionable data makes them a powerful tool in precision agriculture [14].

- *Ultrasonic Sensors*

Ultrasonic sensors use sound waves to measure distances, and they are often used in conjunction with other sensors to provide additional data on crop height, canopy density, and the spatial arrangement of plants. In agriculture, ultrasonic sensors are commonly used for monitoring crop growth and development, particularly in crops where height and canopy structure are important indicators of health and yield potential. By measuring the time, it takes for sound waves to bounce back from the crop canopy, ultrasonic sensors can create detailed profiles of the vegetation. This data can be used to assess crop uniformity, detect areas of uneven growth, and optimize planting density. Ultrasonic sensors are particularly useful in automated farming systems, where they can be integrated with other technologies to provide real-time data on crop conditions [15].

- *Chemical Sensors*

Chemical sensors are used to detect specific compounds in the environment, such as soil nutrients, pesticides, and pollutants. These sensors are often deployed on drones to collect data on soil and plant chemistry, providing farmers with detailed information on the nutrient status of their fields and the presence of harmful substances.

In precision agriculture, chemical sensors are used to monitor soil health and fertility, enabling farmers to apply fertilizers more efficiently and reduce the use of chemical inputs. By detecting the presence of specific nutrients or contaminants in the soil, these sensors help farmers make informed decisions about crop management, improving yields and promoting sustainable farming practices. Additionally, chemical sensors can be used to monitor air quality and detect the presence of pesticides or other chemicals in the environment, providing valuable data for ensuring the safety and sustainability of agricultural operations [16].

2.3 Data Collection and Analysis

In drone-based precision agriculture, the process of data collection and analysis serves as the backbone for informed decision-making and optimized farming practices. Drones, equipped with advanced sensors and imaging technologies, traverse agricultural fields, gathering an extensive range of data. This data encompasses various aspects of crop and soil health, environmental conditions, and overall field status. The ability of drones to collect data in real-time is particularly advantageous, as it allows farmers to detect and address issues promptly, such as pest infestations, nutrient deficiencies, or irregular water distribution. Data collected by drones is diverse and rich in detail. High-resolution visual data provides clear images of the crops, revealing growth patterns, color variations, and the presence of weeds or pests. Spectral data, obtained through multispectral and hyperspectral sensors, offers insights into plant health by detecting variations in light absorption that are invisible to the human eye. This information is crucial for calculating vegetation indices, like the Normalized Difference Vegetation Index (NDVI), which helps in identifying areas of the field under stress due to factors like disease or nutrient deficiencies. Thermal data collected by drones can highlight temperature variations across the field, helping to monitor soil moisture levels and detect areas that may require irrigation adjustments. Additionally, drones equipped with LiDAR sensors generate detailed topographic data, essential for understanding the field's terrain, assessing erosion risks, and designing efficient irrigation systems. Some drones are even capable of collecting chemical data, detecting specific nutrients or pollutants in the soil and air, which can inform decisions on fertilization and pesticide application [15].

Once collected, the vast data undergoes a rigorous process of cleaning, integration, and analysis. This is where the raw data is transformed into actionable insights. The preprocessing stage is critical, as it involves correcting any errors, removing noise, and aligning the data for accurate analysis. The integration of different data types (visual, spectral, thermal) allows for a comprehensive understanding of the field's conditions. For instance, by overlaying NDVI maps with visual imagery, farmers can correlate areas of visible crop stress with underlying causes, enhancing the precision of their interventions.

Advanced analysis techniques, geographic information systems (GIS) and machine learning, play a significant role in extracting valuable insights from the data. GIS tools enable the spatial analysis of data, helping to identify patterns and relationships that are geographically significant, such as areas prone to disease or sections of the field with nutrient deficiencies. Machine learning algorithms, on the other hand, can predict outcomes based on historical data and current observations. For example, these algorithms can forecast crop yield or detect early signs of disease, providing farmers with the information needed to take preemptive measures [16].

The ultimate goal of this extensive data and analysis process is to apply the insights to enhance farming practices. For instance, precision irrigation systems can be fine-tuned based on soil moisture data, ensuring that water is delivered only where it is needed, thereby conserving resources and improving crop yields. Similarly,

data on soil nutrient levels can guide targeted fertilization efforts, reducing the overall use of chemicals and minimizing environmental impact. Early detection of pests and diseases, made possible through detailed data analysis, allows for timely and targeted interventions, reducing crop loss and the need for widespread pesticide use. Additionally, by integrating and analyzing data over time, farmers can predict yields more accurately, aiding in better planning for harvest and market strategies [17].

Applications of Drones in Crop Monitoring

3.1 Assessing Crop Health

Drones have revolutionized the way farmers assess crop health, providing a level of detail and efficiency that was previously unattainable. Imagine being able to monitor your entire field from above, detecting issues that aren't visible to the naked eye. That's the power drones bring to agriculture. They are equipped with an array of sensors that can capture high-resolution images, measure temperature variations, and even analyze light reflection to determine the health of crops. But how exactly do these drones help farmers keep their crops in peak condition? One of the key ways drones assess crop health is through multispectral and hyperspectral imaging. These advanced sensors allow drones to capture data across different wavelengths of light, including those outside the visible spectrum. What does this mean for farmers? It means they can spot issues like nutrient deficiencies or disease long before they become visible to the human eye. For instance, multispectral sensors can calculate the Normalized Difference Vegetation Index (NDVI), which measures the difference between near-infrared and visible light reflected by crops. A lower NDVI value might indicate that a portion of the field is under stress, perhaps due to insufficient water or nutrients. This early warning system enables farmers to take corrective action before the problem spreads, potentially saving an entire season's yield [11].

Thermal imaging is another powerful tool in the drone arsenal. By detecting temperature variations across a field, thermal sensors can identify areas where crops might be under stress due to water shortages or disease. Why is this important? Because temperature differences often correspond to differences in soil moisture or plant health. Cooler areas might indicate adequate water supply, while warmer spots could suggest that plants are struggling due to lack of moisture. This information allows farmers to optimize irrigation, applying water only where it's needed and reducing waste - a crucial step in sustainable farming practices [1]. Moreover, drones provide a level of coverage and detail that manual inspections simply can't match. A farmer might walk through a field and check a few spots, but a drone can cover the entire area in a fraction of the time, providing a comprehensive view of the crop's health. This efficiency doesn't just save time; it also ensures that problems are detected early, reducing the risk of widespread crop failure. The data collected by drones can be processed in real-time, giving farmers immediate insights and enabling quick decision-making [10].

But drones don't just collect data; they help analyze it too. By integrating data from different sensors (visual, spectral, and thermal) farmers can get a holistic view of their crops' health. This integrated approach is crucial because it allows for more accurate diagnoses of problems. For example, if both NDVI and thermal data suggest a problem in a particular area, a farmer can be more confident that the issue is real and not just a sensor anomaly. This level of precision is what makes drone-based crop monitoring so valuable. It turns guesswork into science, helping farmers manage their fields with unprecedented accuracy [17].

The role of drones in assessing crop health is transformative. They offer a bird's-eye view that can detect issues invisible to ground-based inspections. They process data in real-time, enabling swift action. And by integrating various types of data, they provide a comprehensive picture of crop health that can guide targeted interventions. For farmers, this means better crop management, higher yields, and more sustainable practices. The future of agriculture is in the sky, and drones are leading the way.

Drones are proving to be indispensable in identifying pests and diseases in crops, a task that has always been challenging for farmers. The traditional approach often involved manual inspections, which were time-consuming and prone to human error. How many times has a pest infestation gone unnoticed until it's too late? Drones, with their advanced imaging technologies, are changing that narrative by providing early and accurate detection of pests and diseases, allowing for timely interventions.

Drones equipped with high-resolution cameras and multispectral sensors can fly over fields, capturing detailed images that reveal subtle changes in crop appearance. These changes might be early signs of pest infestations or diseases. For instance, a drone can detect color changes in leaves that indicate the presence of a fungal infection, long before it becomes apparent to the naked eye. Multispectral imaging goes a step further by analyzing light reflection at different wavelengths, helping to identify stressed plants that may be under attack by pests or suffering from disease [18]. This early detection is crucial because it allows farmers to target specific areas for treatment, reducing the need for widespread pesticide use and minimizing environmental impact. Another fascinating application is the use of drones to monitor insect activity. Certain types of pests, like aphids or

caterpillars, cause damage that can be visible from above. Drones can be programmed to scan for these signs of activity, identifying areas where the pests are most concentrated. By combining these visual indicators with thermal imaging, drones can also detect changes in plant temperature that might indicate pest-related stress. For example, a patch of crops that appears cooler than the surrounding area might be infested with a pest that disrupts normal plant processes. This layered approach (using both visual and thermal data) provides a comprehensive picture of pest and disease threats, enabling more effective management strategies [19]. Moreover, drones can help in tracking the spread of diseases across large agricultural areas. Once a disease is detected in one part of a field, drones can regularly monitor adjacent areas to ensure it doesn't spread. This capability is particularly valuable in managing viral diseases that can quickly devastate crops if not contained. By keeping a close watch on the progression of such diseases, farmers can take measures to quarantine affected areas or apply targeted treatments, thereby protecting the majority of their crops [20].

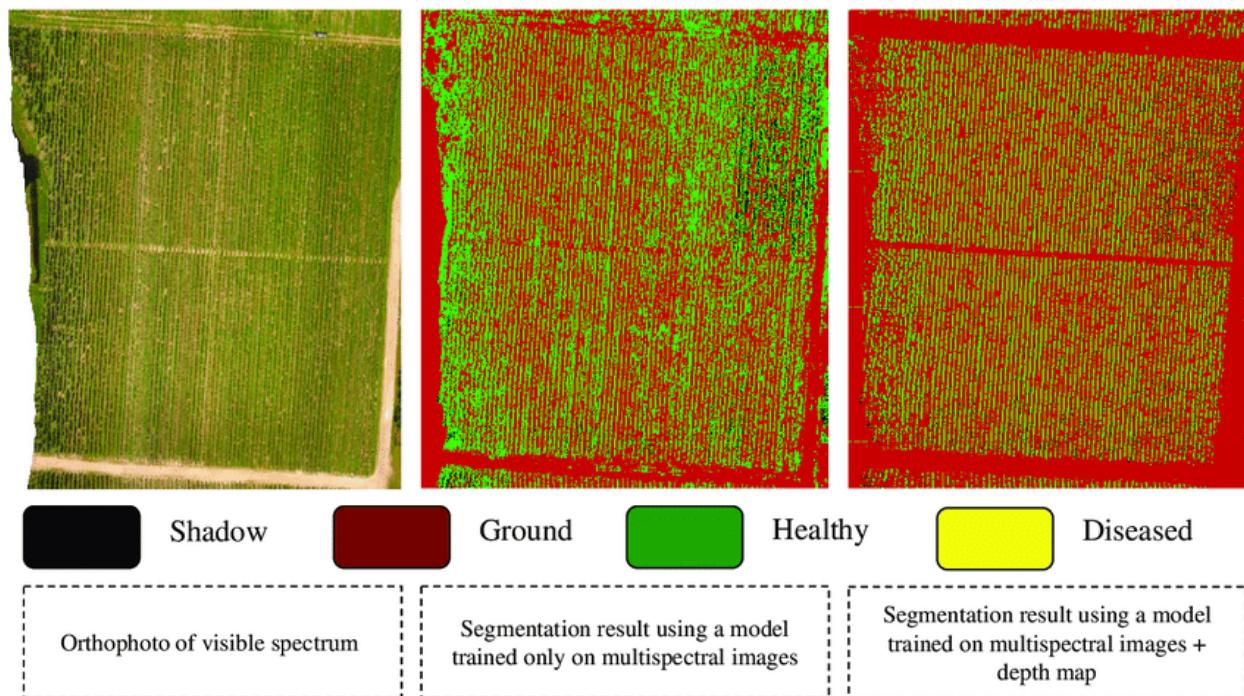


Figure 2 Example of Multispectral Imaging for Crop Health Assessment (The presented example is on an orthophoto of a healthy parcel with a green ground) from [29]

Identifying pests and diseases early not only saves crops but also reduces costs. By using drones, farmers can avoid the blanket application of pesticides, which is often unnecessary and expensive. Instead, they can apply treatments only where needed, leading to more efficient use of resources and better environmental outcomes. Additionally, the data collected by drones can be stored and analyzed over time, helping farmers to identify patterns in pest behavior or disease outbreaks. This long-term data can inform future planting and treatment decisions, further enhancing the sustainability of farming practices [21].

Monitoring soil and water conditions is another critical aspect of crop management where drones are making a significant impact. Healthy soil and adequate water supply are the foundations of successful farming, but monitoring these factors across large fields can be difficult. Drones, however, offer a way to assess soil and water conditions quickly and accurately, providing farmers with the information they need to optimize crop growth.

Using advanced sensors, drones can measure various soil properties, including moisture levels, composition, and temperature. This information is vital for understanding how well crops are likely to grow in different parts of a field. For example, if a drone detects low soil moisture in a specific area, it can alert the farmer to potential drought stress before it becomes a serious issue. This allows for timely irrigation, ensuring that crops receive the water they need to thrive. In some cases, drones can even map out soil composition variations across a field, helping farmers to apply fertilizers more precisely where they are needed most [22].

Water management is equally important, and drones equipped with thermal imaging can be particularly useful in this area. By detecting temperature differences in the soil, drones can identify areas that are too dry or too wet. For instance, a drone might detect a cooler, wetter area in a field, indicating over-irrigation, while a warmer,

drier patch might suggest a lack of water. This real-time data allows farmers to adjust their irrigation systems accordingly, preventing both water waste and water stress in crops. Furthermore, by regularly monitoring soil and water conditions, drones can help to maintain optimal growing conditions throughout the season, leading to healthier crops and higher yields [23].

The integration of drone technology into soil and water monitoring is transforming traditional farming practices. It provides farmers with a detailed, accurate, and dynamic understanding of their fields, enabling them to make more informed decisions. Whether it's detecting early signs of pests and diseases or ensuring optimal soil and water conditions, drones are helping to usher in a new era of precision agriculture, where every decision is backed by data and every action is targeted for maximum efficiency.

Enhancing Crop Management with Drones

The integration of drones into crop management practices has significantly advanced precision spraying and fertilization, two essential components of modern agriculture. Traditional methods of spraying pesticides and applying fertilizers often involve blanket treatments, which can lead to overuse of chemicals, increased costs, and potential environmental damage. Drones, however, offer a more targeted and efficient approach, revolutionizing the way these tasks are carried out.

Imagine a drone flying low over a field, equipped with a sophisticated spraying system that can adjust its output based on real-time data. This is not a futuristic scenario; it's happening now. Drones used for precision spraying are designed to apply pesticides or fertilizers only where they are needed, in the exact amounts required. But how does this work? The process begins with the drone's sensors and imaging systems, which survey the field and collect detailed data on crop health, soil conditions, and pest infestations. This data is then processed to create precise maps that indicate which areas of the field require treatment and how much should be applied [1].

One of the key advantages of using drones for precision spraying is their ability to access hard-to-reach areas. Fields with uneven terrain, densely planted crops, or wet conditions can pose challenges for traditional ground-based equipment. Drones, on the other hand, can easily navigate these environments, ensuring that every part of the field receives the necessary treatment. This not only increases the effectiveness of spraying but also reduces the risk of crop damage that might occur with heavier machinery [12].

The precision that drones bring to spraying is particularly beneficial in reducing chemical usage. By applying pesticides only where pests are detected, drones help minimize the overall amount of chemicals released into the environment. This is crucial for promoting sustainable farming practices and protecting surrounding ecosystems. Moreover, drones can operate with a high degree of accuracy, adjusting the spray pattern and rate in real-time based on factors like wind speed, temperature, and the specific needs of the crops. This level of control ensures that chemicals are applied evenly and effectively, reducing waste and improving crop health [3].

Fertilization is another area where drones are making a substantial impact. Traditional fertilization methods often result in uneven distribution, with some areas receiving too much fertilizer and others too little. This not only wastes resources but can also harm crops and degrade soil quality. Drones equipped with variable-rate technology (VRT) can address this issue by applying fertilizers in precise quantities based on the specific needs of different parts of the field. By analyzing data from multispectral or hyperspectral sensors, drones can assess soil nutrient levels and crop growth patterns, allowing for a customized fertilization plan [4].

This targeted approach to fertilization has several benefits. First, it ensures that crops receive the right amount of nutrients, promoting healthier growth and higher yields. Second, it reduces the risk of over-fertilization, which can lead to nutrient runoff and water pollution. By applying fertilizers more efficiently, farmers can lower their input costs while simultaneously enhancing the sustainability of their farming practices. Additionally, the use of drones in fertilization enables farmers to respond quickly to changing conditions. For instance, if a particular area of the field shows signs of nutrient deficiency, a drone can be deployed to apply additional fertilizer precisely where it's needed, ensuring that the crops stay healthy and productive [5].

Drones also offer the advantage of speed and efficiency in both spraying and fertilization. Compared to traditional methods, drones can cover large areas quickly, significantly reducing the time and labor required for these tasks. This is especially important during critical periods of the growing season when timely interventions are crucial for maintaining crop health. The ability to quickly and accurately apply treatments can make the difference between a successful harvest and a disappointing one. Incorporating drones into precision spraying and fertilization not only enhances the efficiency of these processes but also contributes to more sustainable agricultural practices. By reducing chemical usage, minimizing waste, and optimizing resource application, drones are helping to create a more environmentally friendly approach to farming. As drone technology

continues to advance, it is likely that their role in precision agriculture will only grow, offering even greater benefits to farmers and the environment alike.

Drones are playing an increasingly vital role in irrigation management, a critical component of crop management. Traditionally, irrigation has been a labor-intensive and often inefficient process, with water being applied uniformly across fields without accounting for the specific needs of different areas. This approach can lead to overwatering in some regions and under-watering in others, both of which can negatively impact crop health and yield. With drones, however, farmers can now manage irrigation with a level of precision that was previously unattainable. One of the key ways drones improve irrigation management is through the use of multispectral and thermal imaging. These technologies allow drones to capture detailed data on soil moisture levels across large fields. By analyzing the data, farmers can identify areas where the soil is too dry or too wet. For example, thermal imaging can reveal cooler spots in a field, indicating higher moisture levels, while warmer areas may suggest that the soil is dry and in need of irrigation. This information enables farmers to tailor their irrigation practices to the specific needs of their crops, ensuring that each part of the field receives the optimal amount of water [24].

The ability to monitor soil moisture in real-time is particularly valuable during periods of drought or when water resources are limited. Drones can be deployed regularly to assess the moisture status of the soil, allowing farmers to make timely adjustments to their irrigation schedules. This not only helps to conserve water but also ensures that crops receive the moisture they need to grow effectively. Moreover, by preventing over-irrigation, drones help reduce the risk of soil erosion and nutrient leaching, both of which can degrade soil quality over time [25]. In addition to monitoring soil moisture, drones can also be used to assess the overall health of crops, which can provide indirect insights into irrigation needs. For instance, if a drone detects that a particular area of a field is showing signs of water stress (such as wilting or discoloration) it can alert the farmer to the issue, allowing for quick corrective action. This proactive approach helps to prevent water stress from causing significant damage to the crops, thereby improving overall yield and quality [26]. Another advantage of drone-based irrigation management is its ability to integrate with other precision agriculture technologies, such as automated irrigation systems. By combining drone data with automated irrigation controls, farmers can create highly efficient, responsive irrigation systems that deliver water precisely where and when it is needed. This integration not only saves time and labor but also maximizes the efficiency of water use, which is crucial for sustainable farming practices.

Moving on to optimizing harvesting processes, drones are proving to be just as valuable in this area as they are in irrigation management. Harvesting is one of the most critical phases of the farming cycle, and timing is everything. Harvesting too early or too late can lead to significant losses in yield and quality. Drones offer a way to optimize the timing and efficiency of harvesting by providing detailed, real-time information about crop maturity and field conditions.

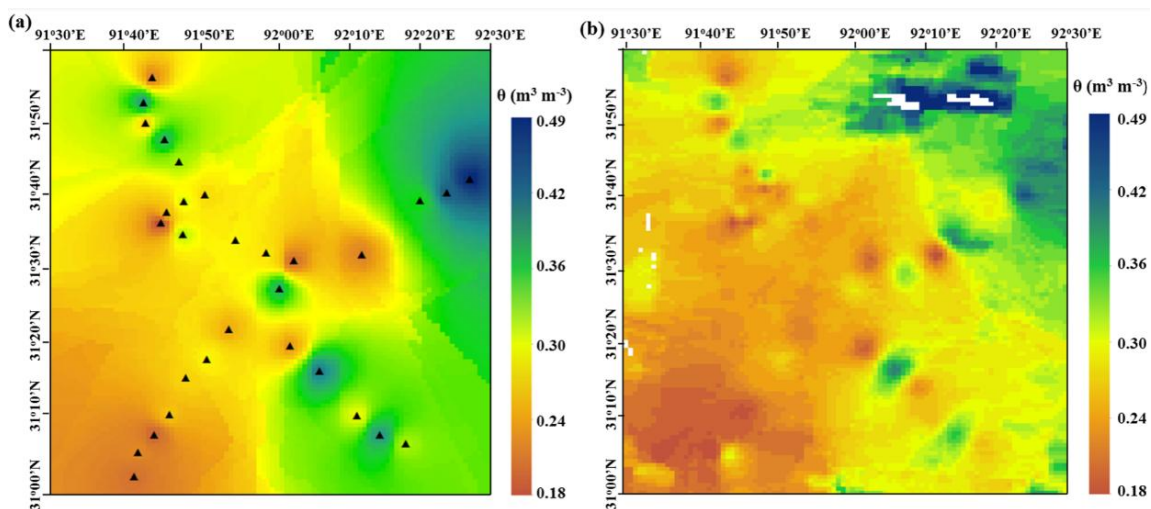


Figure 3 Spatial distribution of surface soil moisture estimated from: (a) the Inverse Distance Weighting (IDW) method; (b) the trapezoidal method. From [30]

Drones equipped with high-resolution cameras and multispectral sensors can survey fields to assess crop maturity with great accuracy. For example, they can detect color changes in the crops, which often indicate

ripeness. By regularly monitoring these changes, drones help farmers determine the optimal time to harvest, ensuring that crops are picked at their peak quality. This is especially important for crops that have a narrow window of optimal ripeness, where even a few days' delay can result in a significant reduction in quality and market value [27].

In addition to timing, drones can also assist in the logistical aspects of harvesting. By mapping out the field and identifying areas where the crops are ready to be harvested, drones can help farmers plan the most efficient harvesting routes. This can save time and reduce labor costs, particularly in large fields where manual planning would be challenging. Moreover, drones can monitor field conditions, such as soil moisture and compaction, which can affect the ease of harvesting. For example, by detecting areas of the field that are too wet, drones can help farmers avoid sending heavy machinery into those areas, preventing soil compaction and crop damage [28]. Drones also contribute to post-harvest management by providing data that can be used to analyze the effectiveness of the harvesting process. For instance, they can capture images of the field after harvest to assess how much of the crop was successfully gathered and whether any was left behind. This information can be invaluable for refining future harvesting strategies, helping farmers to improve their techniques and minimize losses.

Challenges and Limitations

Drones used in agriculture must operate under a variety of conditions, which can present numerous technical and operational challenges. One of the primary issues is the reliability and durability of drones in harsh environmental conditions. Agricultural fields can expose drones to extreme temperatures, humidity, dust, and precipitation, all of which can affect the performance and lifespan of drone components. Additionally, the battery life of drones remains a significant limitation. Most drones have limited flight times, typically ranging from 20 to 60 minutes, which restricts their ability to cover large areas in a single flight. This limitation necessitates frequent battery replacements or recharging, which can be time-consuming and may interrupt critical agricultural operations.

Another technical challenge is the accuracy and reliability of the sensors and imaging systems used by drones. While advancements have been made, ensuring consistent data quality across different environmental conditions remains a challenge. For example, the accuracy of multispectral or thermal imaging can be affected by factors such as cloud cover, sunlight intensity, and wind conditions, leading to potential discrepancies in the data collected. Furthermore, the integration of drone-collected data with existing farm management systems can be complex, requiring sophisticated software and technical expertise. Farmers may face difficulties in processing and analyzing the vast amounts of data generated by drones, limiting the practical usability of the information. Operational challenges also include the need for skilled operators. Flying drones requires not only technical knowledge but also an understanding of agricultural practices. The shortage of trained drone operators in the agricultural sector can hinder the adoption of drone technology, especially in regions where access to training and resources is limited.

Table 2 Technical and Operational Challenges in Drone-Based Precision Agriculture.

Challenge	Description
Environmental Durability	Drones are exposed to harsh conditions such as extreme weather, dust, and moisture, affecting their performance and longevity.
Battery Life	Limited flight times due to short battery life restrict the coverage area and require frequent recharging or battery replacement.
Sensor Accuracy and Reliability	Imaging systems can be affected by environmental factors, leading to inconsistencies in data quality and potential errors in analysis.
Data Integration and Processing	Integrating drone data with farm management systems is complex and requires advanced software and technical skills.
Need for Skilled Operators	Effective operation of drones in agriculture requires specialized knowledge and training, which may not be readily available to all farmers.

Legal and Regulatory Issues

The use of drones in agriculture is subject to a range of legal and regulatory issues that vary by country and region. These regulations are designed to ensure safety, privacy, and security, but they can also create significant barriers to the widespread adoption of drones in farming. One of the most common regulatory challenges is obtaining the necessary permissions to operate drones. Many countries require drone operators to obtain licenses or permits, and there are often strict regulations regarding where and when drones can be flown. For instance, drones may be prohibited from flying near airports, over populated areas, or above certain altitudes. These restrictions can limit the areas where drones can be effectively used in agriculture, particularly in regions close to urban centers or other restricted zones.

Privacy concerns also play a significant role in the regulation of drones. As drones collect detailed images and data from agricultural fields, there is potential for inadvertently capturing images of private property or individuals, leading to privacy violations. This has prompted the development of stringent privacy laws in many jurisdictions, which may impose additional restrictions on the use of drones in agriculture. Another legal issue is the potential liability in the event of a drone accident. Drones are subject to mechanical failures, loss of control, and other unforeseen issues that could result in accidents causing property damage or injury. Liability laws vary by country, but in general, drone operators may be held responsible for any damages caused by their drones, which could lead to costly legal disputes.

Economic Considerations

The economic feasibility of drone-based precision agriculture is another critical factor that affects its adoption. While drones can offer significant cost savings in the long term through increased efficiency and reduced input costs, the initial investment can be substantial. The cost of purchasing high-quality drones, along with the necessary sensors, imaging systems, and software, can be prohibitively expensive for small and medium-sized farms. Additionally, ongoing costs such as maintenance, repairs, software updates, and training for operators add to the financial burden.

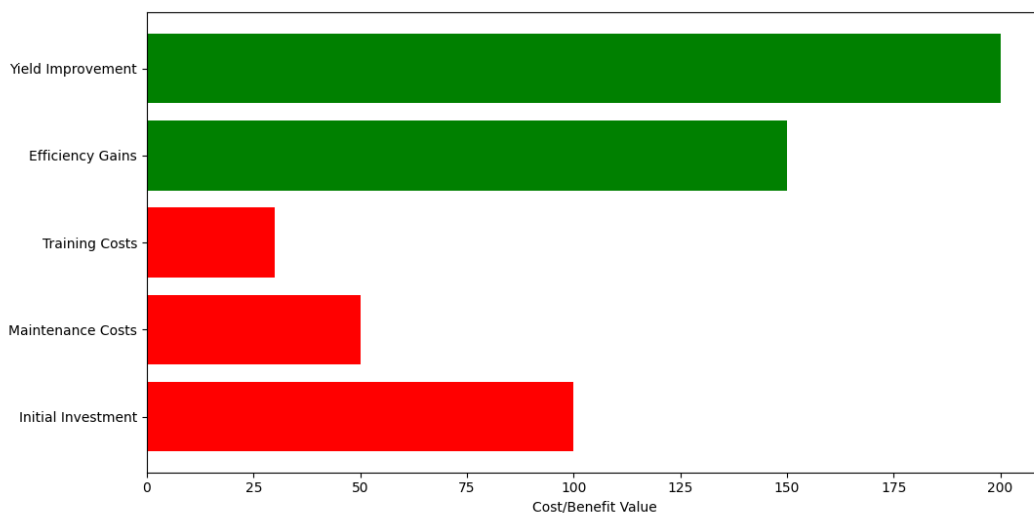


Figure 4 Cost-Benefit Analysis of Drone Adoption in Agriculture.

The return on investment (ROI) for drone technology can vary widely depending on factors such as the size of the farm, the type of crops being grown, and the specific agricultural practices in use. Larger farms with high-value crops may see a quicker ROI due to the scale of operations and the potential for significant efficiency gains. However, smaller farms or those growing low-margin crops may find it difficult to justify the cost, particularly if the benefits of drone technology are not immediately apparent. Furthermore, the economic benefits of drones in agriculture are closely tied to the farmer's ability to effectively utilize the data generated by drones. Without the skills or resources to analyze and act on this data, the potential cost savings and productivity gains may not be fully realized, reducing the overall economic value of the technology.

Table 3 Economic Considerations in Drone-Based Precision Agriculture.

Consideration	Description
Initial Investment	The cost of purchasing drones, sensors, and software can be high, creating a financial barrier for small and medium-sized farms.
Ongoing Costs	Maintenance, repairs, software updates, and operator training add to the long-term financial burden of using drones.
Return on Investment (ROI)	ROI varies based on farm size, crop type, and agricultural practices; larger farms may see quicker returns, while smaller farms may struggle with the costs.
Data Utilization	The economic benefits depend on the farmer's ability to effectively use drone-generated data, requiring technical skills and resources.
Market Accessibility	Limited access to financing and markets for drone technology can hinder adoption, especially in developing regions.

Future Prospects of Drone-Based Precision Agriculture

The future of drone-based precision agriculture is poised for significant advancements, with several exciting prospects on the horizon. One of the most promising areas is the continual improvement in drone technology itself. As drones become more sophisticated, we can expect to see enhancements in flight times, sensor accuracy, and data processing capabilities. Innovations such as artificial intelligence and machine learning are likely to play a critical role, enabling drones to autonomously analyze data and make real-time decisions in the field. These advancements could lead to more precise and efficient agricultural practices, reducing waste and improving crop yields even further.

Another key development will be the integration of drones with other smart farming technologies. As part of a larger ecosystem of connected devices, drones could work in tandem with soil sensors, automated irrigation systems, and weather stations to create a fully integrated, data-driven approach to farming. This convergence of technologies would allow for seamless information sharing and coordinated actions across different aspects of farm management, leading to optimized resource use and better decision-making. For instance, drones could work alongside ground-based sensors to provide a comprehensive view of soil conditions, enabling more precise irrigation and fertilization practices.

The potential impact of these advancements on global agriculture cannot be overstated. As drone technology becomes more accessible and integrated with other smart farming tools, it has the potential to transform agricultural practices worldwide, particularly in regions where traditional farming methods are still prevalent. The scalability of drone-based solutions could help address critical challenges such as food security, water scarcity, and environmental sustainability. By enabling more efficient and sustainable farming practices, drones could play a crucial role in feeding a growing global population while minimizing the environmental footprint of agriculture. This vision of the future is not just about technological innovation but also about creating a more resilient and equitable agricultural system that can adapt to the challenges of the 21st century.

Conclusion

Drone-based precision agriculture represents a transformative approach to modern farming, offering significant advancements in crop monitoring and management. Through the use of advanced sensors, imaging technologies, and data analysis, drones have enabled farmers to enhance the precision and efficiency of key agricultural practices such as spraying, fertilization, irrigation, and harvesting. These innovations not only contribute to increased crop yields and reduced resource usage but also support more sustainable and environmentally friendly farming methods. However, the widespread adoption of drone technology in agriculture is not without its challenges. Technical and operational hurdles, such as limited battery life, the need for skilled operators, and the complexity of data integration, must be addressed to fully realize the potential of drones in this field. Additionally, legal and regulatory barriers, along with economic considerations, can impede the broader implementation of this technology, particularly for small and medium-sized farms. Looking to the future,

continued advancements in drone technology, coupled with their integration into broader smart farming ecosystems, promise to further revolutionize agriculture. As these technologies evolve, their potential to improve global food security, enhance sustainability, and increase agricultural productivity will be critical in meeting the challenges of feeding a growing global population. By overcoming the current limitations and embracing the opportunities presented by drone-based precision agriculture, the agricultural sector can move towards a more efficient, resilient, and sustainable future.

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