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Smart Farming: How Drones Are Transforming the Future of Food Production?

Ehsan Bagheri *, Himan Khodkam

Department of Biosystem Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

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ABSTRACT

Agriculture in the 21st century confronts numerous obstacles, such as increasing population, climate alterations, and resource depletion. Addressing these challenges requires innovative approaches to guarantee food security and sustainability. Drones, or unmanned aerial vehicles (UAVs), have emerged as transformative tools in precision agriculture, offering capabilities such as crop monitoring, pesticide spraying, planting, and soil analysis. Equipped with advanced sensors, GPS, and artificial intelligence (AI), drones optimize resource use, minimize environmental impact, and enhance productivity. They are categorized into fixed-wing, multi-rotor, and hybrid types, each designed for specific agricultural tasks. Despite their potential, widespread adoption faces barriers such as high costs, limited flight duration, and the need for technical expertise. Future advancements in AI, the Internet of Things (IoT), and battery technology are expected to address these limitations, paving the way for more efficient and extensive use of drones in agriculture. Government policies, training programs, and technological innovations play a critical role in promoting drone adoption, particularly in developing regions. By integrating drones into farming practices, agriculture can achieve greater efficiency, sustainability, and resilience, ultimately contributing to global food security and the reduction of hunger.

1. Introduction

Agriculture in the 21st century is facing unprecedented challenges, including rapid population growth (Wei et al., 2024), climate change (Awais et al., 2023), and the degradation of natural resources (Hossain et al., 2020). These factors have placed immense pressure on existing agricultural systems, underscoring the urgent need for innovative solutions to ensure food security and environmental sustainability. With the global population growing rapidly, food production must increase by more than 50% to meet human demands. However, conventional farming methods are insufficient to achieve this goal. As a result, improving production efficiency through the optimized use of resources such as land, water, and labor has become a critical priority (Wei et al., 2024).

While numerous factors—such as climatic conditions, annual precipitation, and the availability of arable land—are often beyond human control, other parameters, including the use of fertilizers and pesticides, seed selection, labor allocation, water management, operation timing, operational losses, labor intensity, and occupational health risks, can be effectively managed and monitored using modern technologies like unmanned aerial vehicles (UAVs) and the Internet of Things (IoT) (Dai et al., 2022). These technologies not only help reduce agricultural inputs and maximize productivity but also empower farmers and contribute to alleviating global hunger. In this context, precision agriculture has emerged as a promising approach to addressing these pressing challenges.

Sustainable soil and water management are critical global concerns. Soils play a central role in achieving the Sustainable Development Goals (SDGs), as they are essential for food security, climate regulation, and biodiversity conservation. Achieving these objectives requires the adoption of more sustainable agricultural practices. Meanwhile, water management in agriculture presents a significant challenge, especially in the face of climate change. Studies suggest that by the end of the 21st century, regions affected by water scarcity will expand significantly. This alarming trend highlights the urgent need to implement more sustainable and water-efficient agricultural practices (Ray et al., 2019).

The impact of climate change on agriculture is already profound and is expected to intensify in the coming years. Evidence indicates that climate change is negatively affecting global food production, with yields of major crops such as maize and wheat declining in certain regions due to changes in temperature and precipitation patterns. In this context, advanced technologies like drones and the Internet of Things

*Corresponding author's email: ehsan.bagheri62@gmail.com

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(IoT) have emerged as essential tools for boosting agricultural productivity and reducing environmental impacts. Through precise crop monitoring using multispectral imaging, targeted application of inputs, and high-resolution data collection, drones enable the optimization of resource use and enhance the resilience of agricultural systems to climate change (Singh et al., 2024). The integration of artificial intelligence (AI) and the Internet of Things (IoT) with drone technologies has opened new avenues for more precise and sustainable agriculture. These technological advancements promise to revolutionize crop management, data-driven decision-making, and resource optimization in the agricultural sector (Mahroof et al., 2021).

This study is a review of studies and research conducted, with up-to-date articles obtained from the reputable sites Science Direct and Google Scholar. This article aims to explore the role of drone technology in transforming agriculture and enhancing food production methods. By focusing on the diverse applications of drones in precision agriculture—such as pesticide spraying, planting, harvesting, crop health monitoring, and soil and water resource management—this article seeks to identify current challenges and propose innovative solutions to increase productivity, reduce costs, and minimize negative environmental impacts. Additionally, it examines future prospects, including the integration of artificial intelligence (AI) and the Internet of Things (IoT) in drones, as well as the role of government policies and education in promoting the global adoption of this technology. The pros (Positive effects) and cons (Negative effects) of using drones in agriculture are shown in Fig. 1.

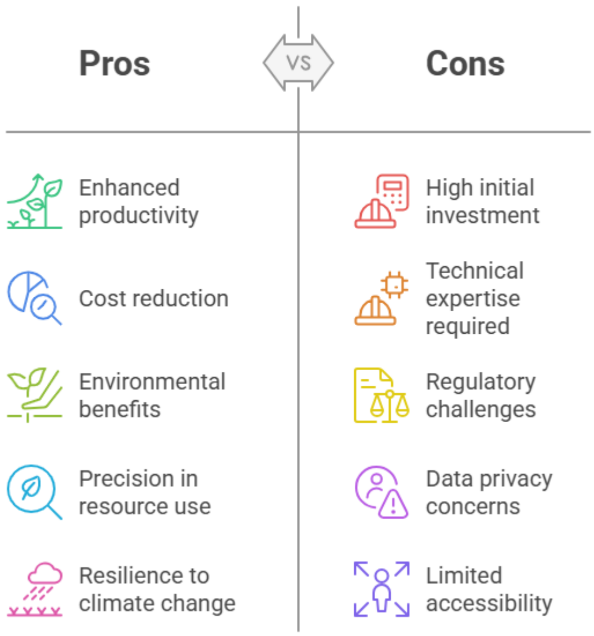

Fig. 1. Pros and cons of using drones in agriculture

2. Method

This review article was conducted to collect and systematically analyze previous studies. Initially, a comprehensive search was carried out in reputable databases, including PubMed, Scopus, Web of Science, and Google Scholar, using keywords relevant to the article's topic. Boolean operators (AND, OR, NOT) were employed to refine the search and improve its accuracy. After the initial screening, the full texts of the selected articles were thoroughly reviewed, and data related to general study information, methodology, key findings, and concepts were extracted. Qualitative analysis methods were used to analyze the data, with findings categorized and interpreted based on recurring themes. For studies containing quantitative data, descriptive statistical methods were applied to summarize the results.

3. Agricultural Drone

Initially developed for military applications, drones have undergone significant advancements in agricultural use since the 1980s. Drones, also known as unmanned aerial vehicles (UAVs), are remotely controlled by human operators and are capable of hovering, taking off, and flying using rotors (propellers). Their operation relies on the generation of thrust and lift through these rotors, enabling them to ascend and maneuver in the air. Additionally, drones are equipped with internal sensors and advanced navigation systems, such as GPS, which facilitate remote control or autonomous flight through embedded software programs (Laghari et al., 2023). As advanced tools in precision agriculture, agricultural drones possess unique features that make them ideal for a wide range of agricultural applications. These drones are typically equipped with advanced sensors, such as spectral (multispectral), thermal, and LiDAR, enabling plant monitoring, multi-soil surveying, pest and disease detection, and even environmental stress assessment. Additionally, agricultural drones can perform tasks such as precision spraying, seeding, harvesting, and 3D field mapping. Utilizing advanced navigation systems like GPS and GNSS, these drones carry out their operations with exceptional accuracy. Moreover, by minimizing the use of pesticides and fertilizers, drones not only reduce costs but also offer significant environmental benefits. Given their versatile and efficient capabilities, agricultural drones are emerging as a key tool for enhancing productivity, lowering costs, and promoting sustainable agriculture.

4. Materials and Design

Drones are constructed from lightweight and durable materials to optimize flight performance. Common materials include carbon fiber and Kevlar, which are widely used due to their lightweight properties and high strength. Composite materials, made by combining fibers (such as carbon or glass) with resins, are also extensively utilized in the manufacturing of drone components. Aluminum is frequently used for the frame and certain structural parts. These materials not only reduce the overall weight of the drone but also provide the necessary strength and durability, thereby enhancing flight performance and efficiency (Balaji et al., 2022). Aerodynamic designs play a critical role in improving energy efficiency and extending flight time. Drones consist of various components that, when assembled, work together seamlessly to perform assigned tasks in the most effective manner.

4.1. Battery

Lithium-polymer (LiPo) batteries are predominantly used in drones due to their lightweight nature and high energy density. These batteries can deliver high voltage, which is essential for powering various drone components, including motors, sensors, microcontrollers, and cameras. Additionally, LiPo batteries enable longer flight times and optimal performance, thanks to their flexible design and fast-charging capabilities (Makam et al., 2024). However, proper temperature management and charging practices are crucial to prevent issues such as swelling or fire hazards. For this reason, the integration of battery management systems (BMS) in drones has become standard practice to enhance safety and efficiency. As technology advances, next-generation batteries with higher capacity and reduced weight are expected to revolutionize the drone industry.

4.2. Flight Duration

Flight time, or autonomy, is one of the most critical factors in drone performance and can vary significantly. Drones can remain airborne for anywhere between 20 minutes to several hours, depending on their design, battery type, environmental conditions, and payload weight. For instance, lightweight drones equipped with lithium-polymer (LiPo) batteries typically have shorter flight times, whereas larger drones with more advanced systems can stay airborne for extended periods. Payload weight is a key factor influencing flight time, as heavier loads require more energy for lift-off and altitude maintenance, thereby reducing flight duration. In agricultural drones, payload capacity ranges from a few hundred grams to several kilograms, depending on the drone's size, type, and application. For example, smaller drones may only carry pesticides or light fertilizers, while larger drones can transport heavier equipment such as sensors or larger tanks. In addition to payload weight, factors such as wind speed, temperature, and altitude can also impact flight duration (Makam et al., 2024). Consequently, drone manufacturers are continuously working to extend flight times by improving designs, utilizing lighter materials, and optimizing energy systems. These advancements are particularly crucial in fields such as agriculture, surveillance, and cargo delivery, as longer flight times translate to greater efficiency and reduced operational costs.

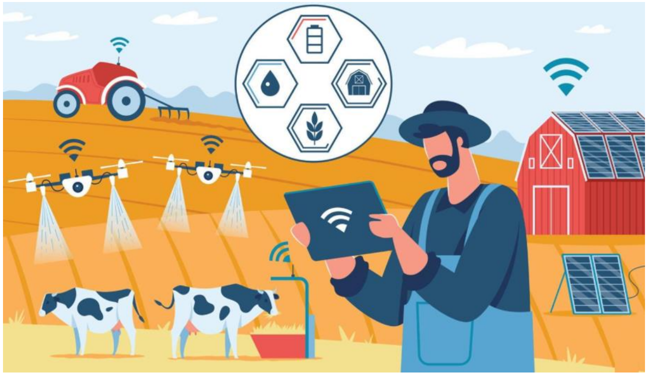

Fig. 2. A schematic of how an agricultural drone works and operates

4.3. Sensors

The primary function of sensors is to collect data and transmit signals to the microcontroller (Prakash et al., 2023). Sensors transmit signals in two forms: digital and analog. Analog signals are continuous and represent measurements that change over time, such as temperature, light intensity, accelerometer readings, gyroscope data, speed, and direction. In contrast, digital signals are discrete and are used to measure specific physical quantities, such as leaf moisture, soil nitrogen, phosphorus, and potassium (NPK) levels, and pH (Mao et al., 2020). Analog sensors are particularly useful for monitoring motion-related parameters (Channe et al., 2015). Fig. 2 illustrates an agricultural drone.

5. Navigation and Control Systems

5.1. Precise GPS/GNSS

GPS/GNSS (Global Positioning System) plays a crucial role in precision agriculture. This technology utilizes a network of satellites to determine the precise location of agricultural machinery, drones, and other equipment with accuracy down to centimeters. High positioning precision enables operations such as planting, fertilizing, and spraying to be carried out with exceptional accuracy. This not only enhances productivity and reduces costs but also minimizes adverse environmental impacts. Drones equipped with GPS/GNSS can identify target areas with high precision and perform necessary tasks efficiently. Additionally, these systems provide farmers with accurate data, enabling better analysis and informed decision-making (Radoglou-Grammatikis et al., 2020). As technology continues to advance, the accuracy and efficiency of GPS/GNSS systems are expected to improve further in the future.

5.2. Inertial Measurement Units (IMUs)

Inertial Measurement Units (IMUs) are essential components in the navigation systems of drones and unmanned aerial vehicles (UAVs). These systems utilize sensors such as gyroscopes and accelerometers to measure the angular and linear movements of drones in three dimensions. IMU data enables drones to maintain their position and orientation, particularly when GPS signals are weak or unavailable. By integrating IMU and GPS data, drones can achieve precise and stable navigation, even in complex environments or adverse weather conditions. This integration enhances drone performance in applications such as mapping, surveillance, and search and rescue operations. Additionally, IMUs play a vital role in stabilizing flight and minimizing unwanted vibrations and oscillations. Recent advancements in IMU technology have significantly improved the accuracy and reliability of these systems. As a result, drones are now better equipped to perform in sensitive applications, including precision agriculture, environmental monitoring, and goods delivery (Toscano et al., 2024).

5.3. Obstacle Detection Systems

Obstacle detection systems are a critical and advanced feature in modern agricultural drones, significantly enhancing the safety and efficiency of operations. These systems typically employ LiDAR sensors, stereoscopic cameras, or ultrasonic sensors to detect obstacles in the drone's flight path. LiDAR generates a 3D map of the environment by emitting laser pulses and measuring their return time, while stereoscopic cameras calculate the depth and distance of obstacles using dual lenses. These technologies enable drones to autonomously avoid collisions with both stationary and moving obstacles, such as trees, buildings, or animals. In complex agricultural environments—such as fields with uneven terrain or densely vegetated areas—these systems play a crucial role in preventing damage to both the drone and crops. Additionally, obstacle detection systems allow UAVs to operate autonomously with high precision, even in low-visibility or low-light conditions (Farhan et al., 2024). This capability is particularly valuable during nighttime operations or in areas with dense foliage. As technology continues to advance, these systems are becoming increasingly sophisticated, enabling them to detect and respond to dynamic obstacles such as birds or moving machinery. Consequently, integrating obstacle detection systems into agricultural UAVs not only improves operational safety but also enhances productivity and accuracy in tasks such as spraying, crop monitoring, and data collection.

5.4. Microcontroller/ Flight Controller

The microcontroller serves as the processing and control unit of the electronic system. It consists of a processor to process sensor data, memory to store data for display, and input/output (I/O) pins to connect input devices (such as sensors) and output devices (e.g., motors and displays) (Khadatkar et al., 2021). Among these pins, analog pins are used to control the speed of DC motors, while digital pins function as direction pins to manage the clockwise and counterclockwise rotation of DC motors (Sundmaeker et al., 2022). Data is transferred through communication channels such as Bluetooth or Wi-Fi and displayed on the microcontroller.

In UAVs, the microcontroller is integrated into the hardware but is a general-purpose component capable of performing various tasks. Essentially, a UAV requires both a microcontroller and a flight controller (Jha et al., 2019). The microcontroller handles general computational tasks and facilitates communication between various components, while the flight controller specifically manages flight operations, controls motors, and ensures the safe operation of the UAV in the air (Prakash et al., 2023).

5.5. Communication Systems

A communication system/port is a unit that transmits and receives signals between the microcontroller and the remote unit (Beniwal & Singhrova, 2022). These systems enable operators to plan missions, monitor flights in real time, and process collected data (Crusiol et al., 2022). They provide wireless communication between the drone and the remote controller for data transfer, configuration, and software updates (Haseeb et al., 2020). Among these ports, RF (Radio Frequency) and IR (Infrared) ports are primarily used for internal purposes, such as controlling indoor devices like TVs and air conditioners (Jain et al., 2021). In contrast, Bluetooth and Wi-Fi ports are employed for external applications, including the control of Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs) (Boursianis et al., 2022). Meanwhile, GSM ports are utilized for controlling UGVs, UAVs, and robots over longer distances (several miles) (Frauendorf & Almeida de Souza, 2022).

The integration of 4G and 5G networks enables UAVs to operate Beyond the Visual Line of Sight (BVLOS), significantly enhancing their range and efficiency. This advancement creates new opportunities for large-scale surveillance and diverse applications (Hongbo et al., 1985). Mission planning software plays a critical role in optimizing UAV operations. These tools facilitate flight path definition, weather data integration, and the management of surveillance constraints.

5.6. Propulsion Systems (Electric, Hybrid. Combstion)

Engines are most commonly used to rotate the propellers in drones, enabling flight operations. These propellers rotate rapidly, driven by motors, to generate the necessary force and lift, keeping the drone airborne. Brush motors are typically used in smaller drones, while brushless motors are employed in larger UAVs due to their efficiency and durability (Toscano et al., 2024). Batteries are required to power these motors, and they can be charged in various ways. The most common types of batteries used include Lithium-Polymer (LiPo), which is widely favored for its high capacity-to-weight ratio; lithium-ion, which offers good energy density; and $LiFePO_4$ (Lithium Iron Phosphate), which is safer but has lower energy density.

Fig. 3. Fixed-wing drones

Fig. 4. Multi-rotor drones

Most agricultural drones use electric propulsion systems, which provide a good balance between performance and ease of maintenance. However, for applications requiring longer flight times, hybrid systems that combine electric and combustion engines are becoming increasingly popular (Townsend et al., 2020). Innovative hybrid systems are also being developed, such as electric-gasoline hybrid systems that combine a gasoline engine with electric motors, battery-based hybrids that incorporate hydrogen fuel cells alongside batteries, and solar-electric hybrids that use solar panels to recharge batteries during flight. These diverse propulsion options offer greater flexibility in drone design and application, catering to different operational needs and conditions in agriculture.

6. Classification of Drones used in Agriculture

Drones used in agriculture are divided into different categories based on their features, applications, and capabilities. This classification helps to better understand the performance and select the most appropriate type of drone for specific agricultural needs. The following are the most important criteria for classifying agricultural drones:

6.1. Based on Structure and Type of Flight

6.1.1. Fixed-wing Drones

Fixed-wing drones, which resemble conventional aircraft in design, are specifically engineered to cover large areas and perform long-duration missions. Operating at high altitudes, these drones can capture high-resolution and highly accurate images of expansive regions such as agricultural fields, forests, and industrial zones. Their ability to cover vast areas in a short time makes them particularly effective for mapping, environmental monitoring, and natural resource management (Matese et al., 2015). Additionally, fixed-wing drones are ideal for large-scale operations, including monitoring the health of agricultural crops, assessing damage from natural disasters, and inspecting power transmission lines. Compared to multi-rotor drones, fixed-wing drones consume less energy and offer significantly longer flight durations. These advantages have established fixed-wing drones as an indispensable tool in precision agriculture, resource management, and scientific research. Fig. 3 illustrates a schematic of fixed-wing UAVs.

6.1.2. Multi-Rotor Drones

The speed and direction of rotation for each propeller are controlled independently to balance and propel the drone. To maintain system stability, one pair of rotors rotates clockwise while the other pair rotates counterclockwise. To ascend, all rotors must operate at high speed. By adjusting the speed of the rotors, the drone can move forward, backward, and side to side (Rinaldi et al., 2023). When air flows over an aerofoil, pressure is applied, resulting in viscous and drag forces acting on the propeller blades. The high fluid pressure beneath the propeller and the low pressure above it generates an upward force known as lift. This force counteracts the drone's weight and keeps it airborne. The magnitude of the lift depends on the angle of inclination (angle of attack) of the aerofoil or propeller (Laghari et al., 2023).

Multi-rotor drones are ideal for applications that require precision and control, thanks to their multi-engine design and high maneuverability. These drones excel in operations such as precision field spraying, crop inspection, and plant health monitoring. One of their key advantages is their Vertical Takeoff and Landing (VTOL) capability, which enables them to operate in confined spaces and over rough or challenging terrain (Hunt Jr & Daughtry, 2018). Additionally, due to their exceptional stability during flight, multi-rotor drones can perform complex tasks such as high-resolution imaging, 3D mapping, and even transporting small payloads. These features have made multi-rotor drones popular tools in precision agriculture, industrial inspection, and scientific research. As technology continues to advance, these drones have become increasingly intelligent, gaining capabilities such as autonomous flight, obstacle detection, and real-time data processing. Fig. 4 illustrates an example of a multi-rotor UAV.

6.1.3. Hybrid UAV$_S$

Hybrid UAVs combine the features of fixed-wing and multi-rotor UAVs, integrating the advantages of both designs into a single system. Thanks to their fixed-wing capabilities, these UAVs offer longer flight endurance and can cover greater distances. Simultaneously, by leveraging multi-rotor capabilities, they enable Vertical Takeoff and Landing (VTOL), making them suitable for use in confined spaces and over rough terrain (Shamshiri et al., 2018).

This unique combination makes hybrid UAVs highly efficient for applications that require both precision and large-area coverage, such as aerial mapping, environmental monitoring, and search-and-rescue operations. Additionally, these UAVs can perform more complex missions with optimized energy consumption, making them an ideal choice for a wide range of applications across various industries.

6.1.4. Folding Wing Drones

Folding-wing Drones represent a groundbreaking innovation in the drone industry, seamlessly combining the aerodynamic efficiency of fixed-wing drones with the added advantage of portability. These drones are equipped with foldable wings, which significantly reduce their size when not in use or during transportation. This unique feature makes them an ideal choice for users who need to carry drones over long distances or store them in limited spaces, such as farmers, surveyors, and military personnel. The foldable design also enables quick deployment, making them highly practical for time-sensitive operations, including agricultural monitoring, disaster management, and surveillance missions. Their compact form and user-friendly design have contributed to their growing popularity in small and medium-scale applications, particularly in agriculture, where they are widely used for tasks such as crop spraying and field mapping.

Despite their numerous advantages, Folding-Wing Drones are not without limitations. The folding mechanism, while convenient, introduces additional complexity to the drone's design, potentially increasing the risk of mechanical failures or wear and tear over time. Moreover, their compact size often results in a smaller payload capacity compared to larger fixed-wing drones, which may limit their effectiveness for certain tasks. Regular maintenance of the folding mechanism is also essential to ensure smooth operation and longevity. However, for users who prioritize portability and ease of transport, these drawbacks are often outweighed by the drone's flexibility and efficiency. Looking ahead, the future of Folding-Wing Drones appears promising. Ongoing advancements in materials and technology are expected to address many of their current limitations. The use of lightweight and durable materials could enhance their durability and flight performance, while improvements in automation and AI integration may further expand their range of applications. As these innovations continue to evolve, Folding-Wing Drones are likely to become even more versatile and indispensable across various industries. Fig. 5 shows an example of a Folding-wing drone.

Fig. 5. Folding-wing drones

Advantages:

Reduced volume: Easier transportation and storage.

Increased mobility: This can be used in places that are difficult to access.

Time-saving: Quick deployment and preparation for flight.

Disadvantages:

Mechanical complexity: Folding wing designs may require more maintenance and repair.

Cost: The cost of producing and maintaining these drones may be higher.

7. Based on Agricultural Applications

7.1. Surveying Drones

Equipped with advanced cameras and sensors—such as multispectral, thermal, and LiDAR cameras—surveying drones have emerged as a transformative tool in precision agriculture. These drones are capable of collecting accurate, real-time data on critical field parameters, including plant health, soil moisture, chlorophyll content, and vegetation density. By integrating specialized mapping software and GPS technology, they can generate highly detailed 3D maps of agricultural fields. These maps provide farmers with valuable insights into land topography, drainage patterns, soil variability, and areas prone to pests or diseases (Nex et al., 2022).

The data collected by surveying drones plays a pivotal role not only in irrigation and drainage planning but also in formulating comprehensive farm management strategies. This includes determining optimal fertilizer application, identifying low-yield zones, and optimizing crop rotation patterns. By leveraging these advanced technologies, farmers can significantly enhance productivity, reduce operational costs, and increase overall yields. Moreover, surveying drones

Fig. 6. A fixed-wing UAV equipped with a multispectral camera for agricultural surveying, illustrating its key components

Fig. 7. Schematic of spraying drones

enables data-driven decision-making by delivering precise and up-to-date information, marking a significant leap toward sustainable and smart agricultural practices. Fig. 6 illustrates a schematic of a UAV equipped with a mapping camera, highlighting the integration of cutting-edge technology in modern agriculture.

7.2. Spraying Drones

Spraying drones are equipped with tanks and advanced spraying mechanisms designed to precisely apply fertilizers, pesticides, and herbicides to agricultural fields. These drones offer significant advantages over traditional methods, including higher accuracy, reduced chemical consumption, and improved efficiency. They enable uniform and targeted distribution of liquid fertilizers with an accuracy of 90–95%, enhancing nutrient absorption by plants (Altan & Hacıoğlu, 2020). Additionally, by integrating sensors that monitor temperature, humidity, pressure, wind speed, and precipitation, these drones minimize common issues such as chemical washouts and wind drift. One of the key benefits of spraying drones is their ability to ensure uniform distribution of pesticides and herbicides over large areas. Their capability to fly at low altitudes and follow precise flight paths results in consistent coverage, reducing chemical waste and labor costs. Recent advancements in drone technology have led to the development of automated spraying systems, which can navigate fields and apply chemicals based on predefined parameters, further enhancing operational efficiency (Radoglou-Grammatikis et al., 2020).

Spraying drones can cover up to 10 hectares per hour, making aerial spraying up to five times faster than traditional methods (Faiçal et al., 2017). They also reduce pesticide use by up to 40% compared to conventional techniques (Souvanhnakhoomman, 2024), with some studies reporting reductions of up to 45% (Chen et al., 2021), while maintaining or even improving crop yields (Fue et al., 2020). For instance, a study on olive and mango trees demonstrated that early detection of pests and nutrient deficiencies, followed by timely corrective actions, led to a 25% reduction in chemical use and an 18% increase in production (Pansy & Murali, 2023).

Furthermore, the reduced use of fertilizers and pesticides through drone technology minimizes environmental impacts (Song et al., 2024). Recent research has shown that spraying drones can detect weeds with up to 93% accuracy, even in their early growth stages (Abrougui et al., 2022). These capabilities position spraying drones as an invaluable tool for modern, sustainable agriculture.

Fig. 7 illustrates a schematic of spraying drones, highlighting their advanced design and functionality.

7.3. Seeding Drones (Planting)

Seeding drones are specifically designed to plant seeds in large or hard-to-reach areas, enabling precise depth planting with remarkable speed and accuracy (Khuzaimah et al., 2022). Equipped with advanced sensors that monitor temperature, humidity, pressure, wind speed, and precipitation, these drones can predict upcoming weather conditions to ensure optimal planting times (Narayana et al., 2024). Drone-assisted farming has been shown to reduce the need for manual labor by up to 50%, significantly increasing profitability (Huang et al., 2015). Farmers utilizing drones for soil analysis, planting, and spraying have reported a 25% reduction in input costs—including seeds, fertilizers, and pesticides—while maintaining or even enhancing crop productivity (Lan et al., 2010).

A study investigating the effects of drone speed, flight altitude, and environmental conditions (such as wind and humidity) on seed dispersal revealed that these factors play a critical role in the effectiveness of aerial seeding operations. To improve seed success rates, biodegradable seed capsules have been developed to protect seeds upon impact with the ground, thereby enhancing germination rates (Marzuki et al., 2021). Recent technological advancements have integrated

Fig. 8. Schematic of drone seeding (planting)

Artificial Intelligence (AI) into seeding drones, further optimizing the precision planting process. AI enables the selection of the most suitable planting locations by analyzing factors such as topography, drainage, sunlight exposure, and potential plant interactions. This innovative approach aims to significantly improve planting efficiency by optimizing planting density and tailoring seed parameters to the specific conditions of each region.

Fig. 8 illustrates the process of drone seeding (planting), showcasing the integration of advanced technology in modern agriculture.

7.4. Drones for Harvesting Products

In recent years, drones have been developed to enhance the harvesting process, leveraging advanced technologies such as GPS, precision sensors, and artificial intelligence to perform automated and intelligent harvesting operations. These drones are capable of accurately identifying ripe produce and utilizing robotic arms or specialized harvesting mechanisms to execute the harvesting process with exceptional precision and speed. Such innovations hold significant potential for reducing labor costs, increasing harvesting speed, and improving overall efficiency (Ali et al., 2024).

For instance, research has demonstrated that using drones to harvest vegetables can reduce harvesting time by up to 40% and increase overall efficiency by up to 25% (Canicattì & Vallone, 2024). Moreover, harvesting drones are designed to operate in harsh conditions and on rough terrain, making them ideal for accessing remote and difficult-to-reach areas. These technologies also play a crucial role in optimizing resource use and improving product quality by minimizing crop waste and enhancing harvesting accuracy. Given the growing global population and the increasing demand for agricultural production, harvesting drones represent an innovative and sustainable solution. They have the potential to revolutionize the agricultural industry and transform the future of crop harvesting, paving the way for a more efficient and productive farming ecosystem.

8. Level of Automation

8.1. Manual Drones

Manual drones are fully controlled by a human operator and are designed for simple, small-scale applications. Typically smaller and lighter in size, these drones are easy to transport and can be operated by a single person. They are particularly well-suited for activities such as recreational photography and videography, basic inspections, and introductory drone flight training. Manual drones are usually operated via remote control or mobile applications and require relatively minimal skill to use. However, due to their complete reliance on human control, their accuracy and efficiency are more limited compared to automated or semi-autonomous drones. Despite these limitations, manual drones remain widely popular among non-professional users and drone enthusiasts. Their simplicity and ease of use make them an excellent starting point for individuals new to drone technology (Borikar et al., 2022).

8.2. Semi-Autonomous Drones (Semi-Autonomous)

Semi-autonomous drones combine advanced technologies with human control, enabling them to perform certain tasks automatically while still requiring operator guidance. These drones are typically equipped with navigation systems, environmental sensors, and artificial intelligence capabilities, allowing them to maintain safety, avoid obstacles, and follow predetermined paths autonomously. However, for complex decision-making or mission adjustments, the presence of a human operator remains essential. These drones are particularly well-suited for applications such as aerial surveying, industrial inspections, environmental monitoring, and rescue and relief operations. For example, in agriculture, semi-autonomous drones can automatically capture field images, but critical decisions are made based on the data they collect. This blend of automation and human oversight has positioned semi-autonomous drones as a transformative tool across various industries (Borikar et al., 2022).

8.3. Fully Autonomous Drones

The integration of Artificial Intelligence (AI) and Machine Learning (ML) with data collected by drones has unlocked new possibilities for predictive analytics in agriculture. AI and ML are increasingly being utilized to analyze drone-collected data, enabling more precise and efficient decision-making processes. Equipped with advanced technologies such as GPS, AI, and path-planning algorithms, fully autonomous drones can perform complex tasks with minimal human intervention (Oliveira & Silva, 2023).

These drones not only significantly reduce labor costs but also execute tasks with remarkable accuracy and speed. Software platforms like TensorFlow, IBM Watson, and Microsoft Azure AI assist farmers and agricultural engineers in tasks such as crop classification and early disease detection, greatly enhancing the accuracy and efficiency of crop monitoring. As highlighted earlier, this technology also plays a crucial role in minimizing losses and optimizing fertilizer use, contributing to more sustainable and productive agricultural practices.

9. Size and Capacity

9.1. Mini/ Micro Drones

Small drones have found a wide range of applications across various fields due to their lightweight and compact design, making them particularly suitable for limited-scale operations and small farms. These drones are typically used for short-term missions in confined environments, such as small farms, urban areas, or enclosed spaces. Weighing between 2kg and 25kg (including both the drone and cargo), they are highly portable and easy to transport. Additionally, their small size and low weight grant them exceptional maneuverability, allowing them to navigate tight and complex spaces with ease. The production and maintenance costs of small drones are significantly lower than those of larger drones, making them a cost-effective option for personal users and small businesses. However, their limited payload capacity and shorter flight durations make them less suitable for long-term missions or transporting heavy cargo. Despite these limitations, small drones play a crucial role in advancing new technologies and facilitating daily activities, serving as efficient and flexible tools in various applications (Yin et al., 2024).

9.2. Medium Drones

Weighing between 25 and 150 kg (including the drone and its payload), medium-sized drones are capable of carrying heavier payloads and flying longer distances. This makes them ideal for applications such as medium-sized farming, extensive surveillance operations, and various commercial missions. One of their key advantages is the ability to carry advanced equipment, such as high-resolution cameras, multi-purpose sensors, and specialized tools for agricultural spraying or fertilizing. Thanks to their larger battery capacity and aerodynamic design, these drones can remain airborne for extended periods and cover vast areas efficiently.

For example, medium-sized drones can survey hundreds of hectares of land in a short time, collecting detailed data on plant health, soil moisture levels, and pest presence. Beyond agriculture, they are widely used in industries such as energy for inspecting power lines, wind turbines, and solar panels. In disaster relief and emergency operations, medium-sized drones can deliver essential supplies like medicine, food, and communication tools to hard-to-reach areas (Mattivy et al., 2021).

With ongoing technological advancements, these drones are becoming increasingly intelligent, gaining capabilities such as autonomous flight, obstacle detection, and decision-making in critical situations. These features make medium-sized drones highly valuable not only for commercial applications but also for scientific research and sensitive missions. However, due to their larger size and weight, their operation requires legal permits and compliance with aviation regulations, underscoring the need for careful planning and operator training. Overall, medium-sized drones are powerful and versatile tools that play a significant role in transforming various industries, offering a blend of advanced capabilities and operational flexibility.

9.3. Heavy Drones

Heavy drones represent one of the most advanced technological achievements in the field of unmanned aircraft, offering unparalleled capabilities to carry heavy payloads and cover vast areas. Typically weighing over 150kg (including both the drone and its cargo), these drones have found widespread applications across various industries, including industrial agriculture, cargo transportation, rescue operations, aerial mapping, and even military use. In agriculture, heavy drones excel at spreading pesticides, fertilizers, and seeds over large fields with exceptional precision, significantly reducing costs compared to traditional methods. Additionally, their ability to transport heavy loads to remote or inaccessible areas makes them invaluable in regions with limited or underdeveloped road infrastructure.

Technically, heavy drones are equipped with powerful engines, high-capacity batteries, and advanced navigation systems, enabling extended flight durations and the ability to carry substantial payloads. However, their deployment is not without challenges. Legal restrictions, the need for specialized infrastructure, and high maintenance and repair costs can limit their widespread use. Despite these challenges, heavy drones are widely recognized as a transformative tool in modern industries. As technology continues to advance, the applications of heavy drones are expected to expand further, solidifying their role as a cornerstone of innovation in various sectors (Chen et al., 2024). Table 1 provides a classification of unmanned aircraft types globally, while Table 2 outlines the advantages and disadvantages of each category.

10. Type of Sensores and Equipment

10.1. Drones Equiped with Multyspectral, Thermal, and Lidar Sensores

Drones equipped with multispectral, thermal, and LiDAR sensors are revolutionizing the analysis of plant health, soil conditions, and environmental stresses. These advanced sensors enable the early detection of issues before they become visible to the naked eye, allowing farmers to optimize input use, reduce costs, and enhance decision-making. By utilizing these sensors, drones can scan the soil to assess nutrient levels and soil fertility, providing farmers with critical data to select the most suitable cropping patterns (Javaid et al., 2023). Thermal sensors, which typically

Table 1. Classification of drone types

Parameters	Fixed-wing	Single rotor	Multirotor
Weight	**Heavy**	**Heavy**	**Style**
Flight time	1 hour or more	1 hour or more	20-45 minutes
Floating capabilities	It cannot float.	Can float	Can float
Load capacity	2 to 15kg	2 to 25kg	0.2 to 2kg
Expertise is required	Flying is difficult	Flying is very difficult	Easy to use
Key applications	Survey and mapping of the command area	Planting, spraying and harvesting	Surveillance, photography and inspection

Table 2. Comparison of types of drones used in agriculture: advantages and disadvantages

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

operate in the 7.5-14µm wavelength range (thermal infrared), are particularly effective in agriculture. They can detect temperature variations as small as 0.05–0.1°C, enabling the identification of water stress and the assessment of plant health. This capability leads to significant water savings and more efficient resource management (Zhou et al., 2021).

While typical multispectral sensors capture 4-6 distinct spectral bands, generally in the visible (400–700 nm) and near-infrared (700-1000nm) ranges, hyperspectral sensors offer even greater precision. These sensors can capture hundreds of narrow spectral bands, spanning from 400 to 2500nm with a resolution of 2-10nm. This makes them highly effective for assessing plant health and detecting stress at an early stage (Lu et al., 2020). Drones equipped with thermal, multispectral, and hyperspectral sensors, as well as soil and temperature sensors, can detect increased water stress, evapotranspiration rates, and drought conditions. This technology empowers farmers to optimize irrigation schedules and improve water use efficiency without compromising crop yield (Hiraguri et al., 2023).

Numerous studies have demonstrated the effectiveness of drones in creating accurate soil maps using high-resolution imagery. The data acquired through these maps enable farmers to enhance soil diversity, apply necessary amendments, and optimize fertilizer usage. This approach has been shown to increase crop yields by 12% and improve fertilizer efficiency by 15% (Mulla, 2013). Multispectral and thermal imaging technologies, when integrated with drones, provide unique insights into crop health and environmental conditions. These tools allow for the early and accurate detection of

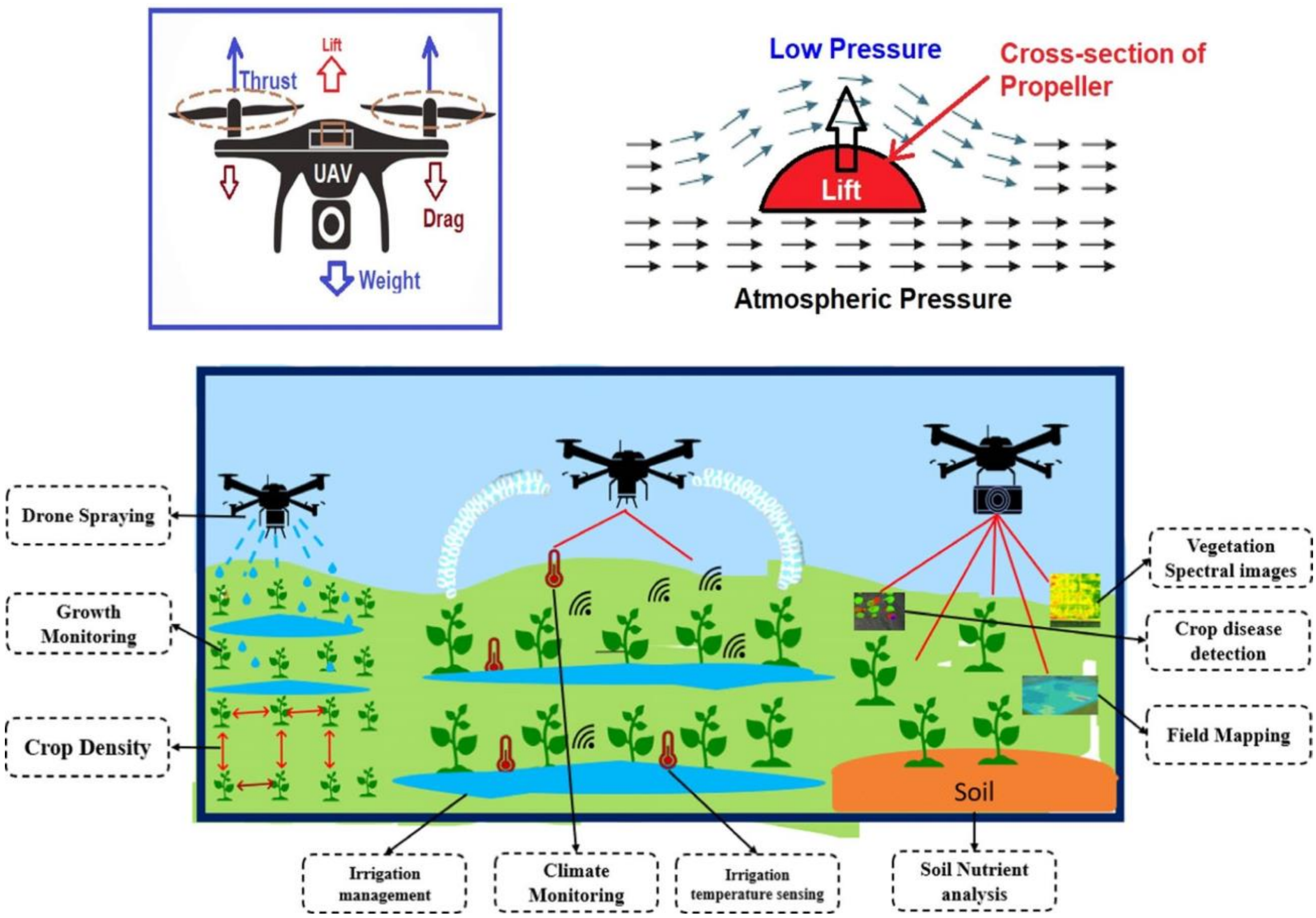

Fig. 9. Application of drones in smart agriculture

plant stress, nutritional deficiencies, and pest infestations. For instance, researchers used visible and thermal images captured by drones to monitor water status by analyzing tree crown growth and olive tree performance under different irrigation regimes. The results revealed a strong correlation between thermal indices and ground-based physiological measurements, demonstrating that drone-based thermal imaging can effectively detect water stress in olive trees. This capability enables more precise irrigation management, improving crop quality and yield while reducing water consumption (Liu et al., 2022).

RGB (Red, Green, Blue) sensors, which operate in the visible light wavelength range of 400 to 700 nm, are commonly used for general mapping and visual crop inspections. In one study, RGB sensors were employed to estimate wheat plant density, achieving a high correlation (R^2 = 0.91) and demonstrating their effectiveness in crop monitoring (Jin et al., 2017).

Drone mapping provides high-precision, high-resolution data that is invaluable for field and crop management. For example, researchers utilized RGB and multispectral images to assess spatial and temporal changes in vineyards. The results highlighted the ability of this approach to analyze the health and vigor of individual vines, offering significant potential for precision vineyard management and the optimization of viticulture practices (Pádua et al., 2020). In another study, a combination of multispectral imaging and deep learning was used for early disease detection in vineyards, achieving 96% accuracy in identifying *Plasmopara viticola* (Kerkech et al., 2020).

LiDAR sensors mounted on drones have revolutionized 3D mapping in agriculture. These systems emit high-frequency laser pulses (up to 1 million points per second) to measure distances accurately and create detailed 3D models of agricultural landscapes (Maimaitijiang et al., 2020). Microwave sensors, operating in the 1–300 GHz range, can penetrate vegetation canopies to provide insights into subsurface soil conditions. These sensors have been used to predict spring soil moisture in snow-affected agricultural areas, accurately measuring snow depth and density to aid in water resource management (Jenssen et al., 2019).

Fig. 9 illustrates the vital role of drones in modern agriculture, showcasing their diverse applications and transformative impact (Makam et al., 2024).

11. Future Vision

To overcome the limitations and make drones more accessible to farmers globally. The following future vision is presented below.

11.1. Traning and Adoption by Farmers

Key barriers to the adoption of drones by small-scale farmers have been identified. The study highlights three main challenges: the lack of technological infrastructure in rural areas, the high initial costs of purchasing and maintaining drones, and insufficient technical skills among farmers. These barriers are particularly significant in developing countries and underscore the need for targeted strategies to promote drone adoption. The findings emphasize the importance of addressing technological, socio-economic, and educational barriers to facilitate the integration of drones into small-scale agriculture (Puppala et al., 2023).

11.2. Traning and Awareness Strategies

A study examining the skills and training needs of civilian drone pilots emphasized the importance of training not only in the technical aspects of piloting but also in ethical and regulatory considerations. In the agricultural context, this necessitates the development of specific training programs tailored to the unique needs of farmers and local conditions (Schmidt et al., 2022).

11.3. Current Technological Limitations

11.3.1. Autonomy and Payload Capacity

Many current drones are limited by short flight durations, typically ranging from 20 to 40 minutes, due to battery constraints. This limitation makes them unsuitable for large-scale farms or extended operations. Additionally, their restricted payload capacity hinders their ability to carry heavier equipment or large quantities of materials, such as pesticides or fertilizers, reducing their effectiveness in certain agricultural applications. Recent studies highlight significant disparities in agricultural drone capabilities between countries. For instance, in developed countries, drones are often equipped with advanced features such as precise navigation systems, high-capacity batteries, and enhanced payload capacities. In contrast, drones in developing countries tend to be technologically inferior, with more pronounced limitations. This technological gap not only exacerbates inequality in access to advanced tools but also poses additional challenges for farmers in disadvantaged regions (Nazarov et al., 2023).

To address these challenges, there is a pressing need to develop technologies such as longer-lasting batteries, fast-charging systems, and innovative designs to increase payload capacity. International collaboration and technology transfer can also play a pivotal role in bridging the technological gap between countries, enabling more equitable access to advanced agricultural tools. By overcoming these limitations, drones can become a more powerful and efficient tool for driving agricultural transformation on a global scale.

11.3.2. Sensor Accuracy and Reliability

The accuracy and reliability of sensors used in drones are critical factors in agricultural applications, especially under challenging environmental conditions. Sensors play a vital role in collecting precise data on plant health, soil moisture, nutrient levels, and other key agricultural parameters. However, their performance is often compromised by environmental factors such as intense sunlight, rain, dust, and temperature fluctuations, which can reduce the accuracy and reliability of the collected data. Researchers have highlighted that the reliability of drone data in varying weather conditions, particularly in regions with unpredictable or extreme climates, remains a significant concern for farmers.

For instance, in hot and arid regions, dust can interfere with the functionality of optical sensors, while in humid areas, rain and high humidity may disrupt the performance of thermal sensors. These challenges underscore the need to develop more robust and adaptable sensors tailored to local environmental conditions (Puppala et al., 2023). To enhance sensor accuracy and reliability, further research is needed to design sensors capable of withstanding harsh environments. This should be complemented by the development of advanced data processing algorithms and automated calibration systems. Additionally, educating farmers on how to correctly interpret collected data and adapt it to local conditions can help build trust in drone technology. By addressing these issues, drones can become a more dependable and effective tool for improving farm management and boosting agricultural productivity.

12. Future Innovations and Promising Research Areas

12.1. Artificial Intelligence and LOT

The integration of AI and machine learning with data collected by drones opens up new horizons for predictive analytics in agriculture. Future research is needed to develop more accurate algorithms that are adaptable to different farming conditions.

12.2. Drones are Swarming

The use of drone swarms represents a transformative advancement in precision agriculture, offering unprecedented efficiency and accuracy in monitoring and managing crops. Unlike single drones, swarms can simultaneously cover vast agricultural fields, collecting synchronized data on crop health, soil conditions, and environmental factors such as temperature and humidity. This real-time, multi-layered data enables farmers to make precise decisions, optimizing irrigation, fertilization, and pest control while minimizing resource waste. For example, a swarm can detect early signs of disease in specific sections of a field, allowing targeted interventions that significantly reduce crop loss. However, deploying drone swarms is not without challenges. Effective coordination and communication between drones are critical to avoid collisions and ensure seamless operation, necessitating advanced algorithms and AI-driven systems. Additionally, energy consumption and battery life remain significant hurdles, as swarms require substantial power to operate over large areas. Researchers are exploring innovative solutions, such as solar-powered drones and wireless charging networks, to address these limitations. Furthermore, regulatory frameworks must evolve to address airspace management, data privacy, and cybersecurity concerns.

Despite these obstacles, the potential benefits of drone swarms—such as increased productivity, reduced environmental impact, and cost savings—make them a promising tool for the future of sustainable agriculture (Ming et al., 2023). As technology continues to advance, drone swarms could become an indispensable asset in meeting the growing global demand for food, paving the way for a more efficient and sustainable agricultural ecosystem.

12.3. Government Policies and Taxincentives

Globally, the Goods and Services Tax (GST) and import duties significantly increase the cost of imported drone components, raising the total cost of drones by 20–30% (Chen et al., 2023). Countries like China and the United States, which possess robust domestic manufacturing capabilities for electronic components, benefit from lower production costs and competitive pricing. In contrast, many other countries rely on importing essential drone components and assembling them domestically, resulting in higher overall costs due to additional taxes and duties. Government subsidies and grants can play a pivotal role in reducing the initial costs of drones for farmers, making this technology more accessible, particularly for small to medium-sized farming operations. To further support this initiative, implementing incentives such as subsidies, tax exemptions, and grants for electronic component manufacturers can stimulate investment and foster growth in this sector. Such measures would promote local production and help reduce the overall costs of drones, making them more affordable and accessible to a wider range of users (Jiang & Xu, 2023).

12.4. Training Program Incentives

The cost of training programs for drone operations varies globally, typically ranging from $500 to $2000 per participant, depending on factors such as the program's comprehensiveness, duration, and the level of certification offered. These programs often cover essential skills, including drone piloting, data analysis, maintenance, and regulatory compliance, all of which are critical for effective drone use in agriculture. However, the high cost of training can pose a significant barrier for many farmers, particularly smallholders in developing regions.

To address this challenge, government-sponsored training initiatives play a vital role in promoting the adoption of drone technology. By subsidizing or fully covering training costs, governments can make these programs more accessible, empowering farmers with the technical expertise needed to operate drones safely and efficiently. Additionally, such initiatives can include hands-on workshops, online courses, and partnerships with agricultural institutions to ensure comprehensive learning. Beyond cost reduction, government support can also provide incentives like grants or low-interest loans for purchasing drones, further encouraging adoption.

Equipping farmers with drone operation skills not only enhances their ability to monitor crops, optimize resource use, and detect issues early but also contributes to broader agricultural productivity and sustainability. Investing in training programs is a strategic move that can accelerate the integration of drones into farming practices, ultimately driving economic growth and food security in rural communities. By prioritizing education and accessibility, governments can unlock the full potential of drone technology in agriculture (He et al., 2023).

12.5. Data Processing Algorithms

The development of a skilled workforce in Artificial Intelligence (AI), Machine Learning (ML), and Image Processing (IP) algorithms is crucial for enhancing data processing capabilities in agricultural drones. Globally, the United States has experienced a significant increase in AI and ML job opportunities, mirroring a broader trend of growing investments in these fields across the European Union and Asia. To fully leverage these advancements, governments and industry stakeholders must prioritize investments in education and training, promote stronger collaborations between universities and industries, and support startups and companies that are developing cutting-edge AI and ML solutions for drone data processing. By improving data processing capabilities, creating advanced software solutions, and reducing operational costs, a well-trained AI and ML workforce can substantially enhance the efficiency and cost-effectiveness of drone technology in agriculture (Seong & Shin, 2024).

13. Conclusions

Agriculture in the 21st century faces unprecedented challenges, including rapid population growth, climate change, and the degradation of natural resources. These issues have placed immense pressure on existing agricultural systems, highlighting the urgent need for innovative solutions to ensure food security and environmental sustainability. In this context, advanced technologies such as Unmanned Aerial Vehicles (UAVs) and the Internet of Things (IoT) have emerged as essential tools for boosting agricultural productivity and reducing environmental impacts. With capabilities such as precise crop monitoring, targeted input application, and high-resolution data collection, drones enable optimized resource use and enhance the resilience of agricultural systems to

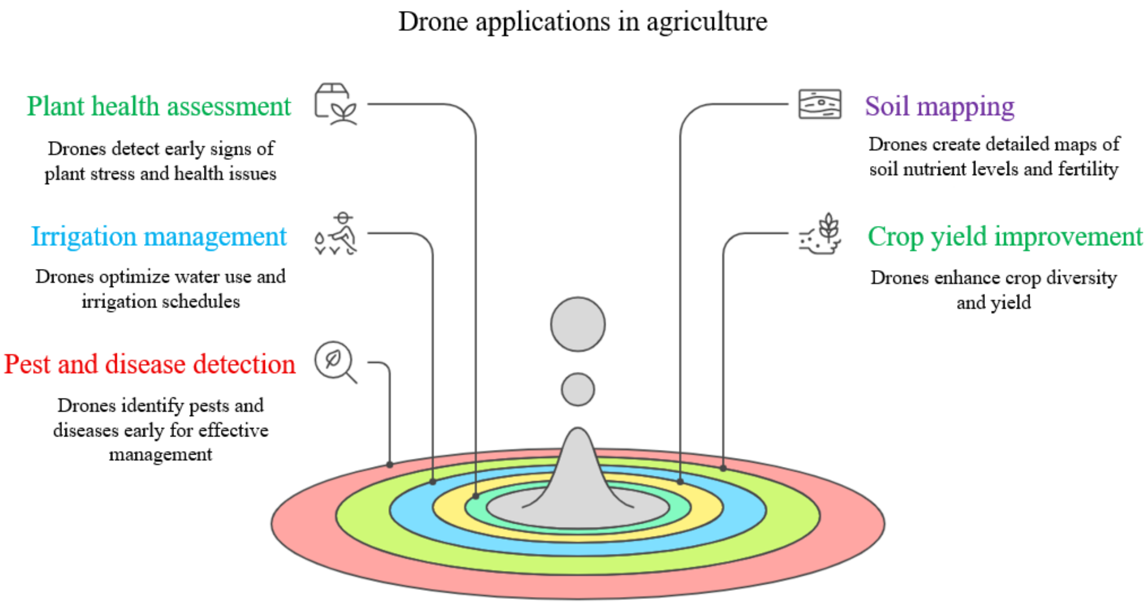

Fig. 10. Application of drones

climate change. The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) with drone technology has opened new avenues for more precise and sustainable agriculture. These advancements promise to revolutionize crop management, data-driven decision-making, and resource optimization in the agricultural sector. However, the widespread adoption of these technologies faces challenges such as high initial costs, the need for training and technical expertise, and technological limitations, including limited drone autonomy and payload capacity. To address these barriers, it is crucial to develop targeted training programs, improve sensor accuracy and reliability, and provide government support through tax incentives and subsidies.

Looking ahead, the integration of Artificial Intelligence (AI) and MachineLearning (ML) with drone-collected data will enable more accurate predictive analysis and advanced agricultural management. Furthermore, the use of drones for efficient monitoring of large agricultural areas and synchronous data collection represents a promising frontier for precision agriculture. With continued technological advancements and government support, drones are poised to play a transformative and versatile role in reshaping the agricultural industry, contributing to food security and environmental sustainability. These technologies will help minimize agricultural inputs, maximize production, and ultimately reduce global hunger. Fig. 10 illustrates the application of drones in this context.

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