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REVIEW ARTICLE

Prospects and challenges of drone technology in sustainable agriculture

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Abstract

Drones have emerged as a viable precision agriculture technology that can help achieve sustainable development goals (SDGs) by enhancing sustainable farming practices, increasing food security and reducing environmental impact. This review paper aims to thoroughly examine the various applications of drone technology, including crop health monitoring, pesticide and fertilizer spraying, weed control and data-driven decision-making for farm optimization. It emphasizes the role of drones in precision spraying, promoting targeted interventions and minimizing environmental impact compared to conventional methods. Drones play a vital role in weed management and crop health assessment. The study emphasizes the relevance of data collected by drones for decision-making concerning irrigation, fertilization and overall farm management. However, using Unmanned aerial vehicles (UAVs) in agriculture faces challenges caused by batteries and their life, flight time and connectivity, particularly in remote areas. There are legal challenges whereby regulatory frameworks and restrictions are present in different regions that affect the operation of drones. With the help of continuous research and development initiatives, the challenges depicted above could be solved and the fullest potential of drones can be tapped for achieving sustainable agriculture.

Keywords

drones; precision farming; standard operating procedures (SOPs); sustainable agriculture

Introduction

The drone was initially created for military purposes and is also called a UAV (1), a miniature pilotless aircraft, or a flying mini robot (2). (UAVs) are aircraft controlled remotely equipped with specialized thermal and multispectral sensors and a Global Positioning System (GPS). Modern drone technology is widely used in military operations, search and rescue, agriculture, mapping, archaeology and wildlife protection (3). Conventional practices suffer from challenges including high use of chemicals, lack of farm labour, uneven distribution of sprays, environmental pollution and incapability of reaching many farms. These conventional approaches consume more money for pesticide application and are less effective in managing pests and diseases (2). However, the current integration of cutting-edge technologies into agricultural systems has initiated a paradigm shift characterized by innovation and increased efficiency in recent years (4). The application of mechanistic and artificial intelligence to farming systems has started the current years of higher innovation and efficiency years sooner (4). Among such incipient innovations, UAVs have become a powerful tool for revolutionizing agriculture. In that regard, drones can capture accurate and high-resolution images, send and supply multiple feeds simultaneously with real-time results and undertake numerous operations in agricultural fields (5). UAVs can revolutionize traditional remote sensing (RS) systems by enabling real-time or condition-specific strategies for plant monitoring, growth analysis, weed detection, crop water stress assessment, disease diagnosis, crop yield evaluation and systematic pest and nutrient management. This depends on what is needed and where the drones will be used, which includes cameras, sensors and control devices.

The use of UAVs in small-scale agriculture, especially in water-stressed areas, is of great value as they provide valuable information for operational decisions at the farm level. It is helpful for risk mitigation against crop failure and low yields (6). Drone data collection is useful to farmers as it can help them manage pests, decide on resource inputs and maximize harvests (7). Continuous monitoring of crops is to detect small changes that may not be easily visible to the human eye (8,9). UAVs equipped with high-resolution multispectral cameras enable precise monitoring of individual plants, ideal for smallholder farms (10). With the help of multispectral images, Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge (NDRE) indices are developed, offering valuable insights into crop health by assessing solar radiation absorption intensity and other critical factors (11). Besides, thermal cameras add value to UAVs' abilities to measure evapotranspiration and identify water stress (12). The spread of UAV use in agriculture is made possible by the reduced cost, with many models now priced affordably despite additional operational expenses (10,13).

Policies are progressively becoming more balanced, particularly in rural areas where safety and privacy concerns are less pronounced (14). UAVs enable rapid reconnaissance of large rural estates, complementing ground-based sensors and surpassing the resolution limitations of satellite imagery (10, 15). Advancements in imaging sensors enable high-resolution aerial images even at high altitudes, making it easier to detect problems early (10). In addition, UAVs are becoming more and more convenient as automated flight missions and offline planning are possible. Drones are crucial in assessing risks and damage in disaster-affected agricultural areas and providing timely information for efficient response and recovery efforts (16, 17). Even when monitoring the impacts of climate change on agriculture, drones offer valuable data for adaptive resource management and crop selection, thereby increasing resilience to future challenges (18).

Drones are a practical, rapid and affordable technology that can gather information on crop emergence, inform decisions about replanting and assist in predicting yield by combining high-resolution data with drones using algorithms for machine learning. This system uses the data to generate output with 97% accuracy acquired using drones and photogrammetry. Drones with Light Detection and Ranging (LiDAR) sensors estimate the possible tree and crop biomass change through differential height measurements (19).

Drone applications for agriculture correspond with multiple Sustainable Development Goals (SDGs). Improving crop monitoring and yield forecasts helps achieve SDG 2: Zero hunger by boosting food security (20). SDG 12: Responsible consumption and production are supported by precision spraying and data-driven interventions since they minimize environmental effects using less pesticide and fertilizer (21). Additionally, by maintaining crop health and optimizing resource use, drones assist SDG 13: Climate action through climate-smart agriculture (22). SDG 15: Life on land is related to their work in enhancing land management and protecting ecosystems (22) and SDG 9: Industry, innovation and infrastructure are related to their promotion of agricultural innovation (23). Collectively, these technologies support sustainable farming methods that help achieve several SDGs.

The structure of this review is meticulously framed to offer a comprehensive understanding of the usage of drones in sustainable agriculture. The main goal of this review article is to examine the inherent potentials and drawbacks associated with drone technology to support sustainable agricultural practices. The aim is to reveal the latent benefits and limitations of using drones in agroecosystems by analyzing and evaluating the potential of unmanned aerial vehicle technology in various agricultural environments and functions, including crop monitoring, pest control, precision agriculture, and sustainable land management. Additionally, we have conducted an in-depth analysis of the technical and regulatory dynamics that govern the adoption and use of drone technology in agriculture, providing insights into the myriad opportunities and obstacles that chart the path to fully realizing its transformative potential.

Types of Drones Used in Agriculture

In terms of agriculture, three primary classifications of (UAVs) are prevalent. These include Fixed-wing, Helicopter and Multi-copter (Fig. 1) (24). This implies a need to consider factors such as the type of UAV model that will suit a given application and the financial resources available. For example, blimps have huge useful characteristics, including hovering and high-reward crowds and their suitability in vertical flight and lift. However, their utility is hampered by inherent limitations such as reduced speed and compromised stability in adverse

Fixed-wing Helicopter Multi-copter

Fig. 1. Primary types of UAVs (1).

weather conditions, which can impede accurate data acquisition (25).

Fixed-wing drones have immobile wings shaped like airfoils, generating lift as the vehicle attains a specific velocity (26). These UAVs are distinguished by their high-speed flight capabilities and prolonged endurance in the air (27). Typically capable of achieving velocities ranging between 25-45 mph, fixed -wing drones exhibit a significant coverage capacity from 500 to 750 acres per hour, contingent upon battery specifications (4).

Helicopters, on the other hand, are rotorcraft with a single set of spinning rotor blades attached to a central mast, creating lift and often incorporating a tail or counter-central rotor for yaw control. Unmanned helicopters possess the capability of vertical take-off and landing, sideways flight and hovering. They boast a larger payload capacity than multi-rotor UAVs, enabling them to accommodate sizable sensors like LIDAR (28). Multi-copters, alternatively, are rotorcraft equipped with multiple rotor blades, typically numbering between 4 to 8, facilitating enhanced control over movements encompassing yaw, roll and pitch (26). This configuration grants multi-copters heightened agility and manoeuvrability, making them particularly well-suited for applications demanding intricate aerial operations within confined spaces or complex environments.

Multi-copter UAVs provide advantages such as cost-effectiveness, hover capability and minimal requirements for take -off and landing, making them extensively utilized for field-based photography (FBP). However, they are accompanied by notable drawbacks, including limited flight duration, diminished payload capacity and vulnerability to adverse weather conditions (29). The advantages, disadvantages and applications of fixed-wing drones, helicopters and multi-copters are represented in Table 1.

Crop-specific Standard Operating Procedures (SOPs) for Drone Applications

Standard Operating Procedures (SOPs) tailored to specific crops and environmental conditions are crucial for maximizing agricultural productivity and ensuring sustainable practices. The Ministry of Agriculture and Farmer's Welfare, supported by the Government of India (GOI), has taken progressive measures to promote the use of drones in agriculture. As part of these efforts, GOI has developed the (SOPs) for drone spraying in agriculture. Crops are grown in various environments, so SOPS must address ecological factors like temperature, humidity, wind speed, terrain and other environmental factors. These SOPs are focused on the drone specifications such as flying speed and height above the crop canopy, sprayer factors including the type of nozzle, spray width, crop factors volume of the canopy and growth stage, water and pesticide rates and the best time to spray.

Furthermore, they also consider the regions' weather and the climate zone where the chemicals are used to obtain the best efficiency of pesticides and to minimize the negative impact on crops. The flying height of the drone over the crop canopy depends on aspects like the total mass of the drone, the downforce impact over the crop canopy and the type of sprayer. To ensure operational efficiency and safety concerns, the drone is programmed to work at the optimal level below the crop canopy to avoid drift when spraying. Nevertheless, it is indispensable to keep the vertical clearance above the crop because the thrust of the drone may be detrimental to the crop. Hence, the appropriate height for operation has been highlighted in the SOPs. Likewise, the speed of the drone's flying is associated with the spray distribution pattern and should also be optimized. Several experiments have been conducted to standardize the drone application among different crops, delineated in Table 2.

Rice

Rice is the most important staple crop cultivated in large areas of Asia and other continents. It requires an SOP for drone application to achieve the fullest potential of drones in rice crop monitoring. Hence, Tamil Nadu Agricultural University in Coimbatore, India conducted a pioneering study on using drones for pesticide spraying in rice fields. They utilized a hexacopter drone with specific parameters, including a payload of 16 L and a fuel capacity of 3.5 L. Through this study, they established a standard operational protocol for drone-enabled pesticide application, determining that a flight height of 1.5-2.0 m, a flight speed of 5m s^{-1}, the area coverage (4 min/acre) and a wind speed

Table 1. Benefits, drawbacks and applications of fixed-wing drones, helicopters and multi-copters

Types of drones	Payload & Applications in Agriculture	Benefits	Drawbacks	Reference
Fixed wing	1. Large-scale spraying 2. Monitoring extensive areas 3. Crop growth assessing 4. Crop health status 5. Fertilizer and pesticide spraying.	1. Streamlined architecture 2. Simplified maintenance 3. Increased flight speed 4. Enhanced energy efficiency 5. Superior survivability	1. Restricted accessibility 2. Reduced wind resistance 3. Challenges in launching and landing 4. Required more training 5. Initial and maintenance costs are high	(2)
Helicopters	1. Spraying capacity (5 to 30L) 2. Pesticide spray 3. Estimation of crop height 4. Soil and field analysis 5. Crop classification	1. Longer time in flying 2. Increased speed 3. Robust durability, 4. Accessibility to remote locations and operating on petrol. 5. Vertical take-off, landing, hovering, forward, backwards.	1. Incomplete coverage during spraying 2. Increased weight 3. Expensive setup 4. Stability issues 5. Initial and maintenance costs are high	(2, 30)
Multi–copter	1. Spraying (up to 10L) 2. Local field requirements and crop stress, targeted pesticide spraying 3. Monitoring small fields, estimating crop height 4. Conducting soil and field analysis 5. Integral aspects of the overall agricultural approach.	1. Tailored site management. 2. Low-altitude flight improved stability. 3. Stable flight, increased payload, slow capability. 4. Vertical take-off, UAV swarms. 5. Pre-programmed flight plans and improved accessibility	1. Limited by slow speed 2. Payload weight capacity 3. Complex architecture and challenging maintenance procedures 4. Limited flight capabilities 5. Unstable in weather	(2), (30)

Table 2. Application of UAVs with the set of parameters (spraying width, flight height, flight speed, nozzle type) in various crops

Crop	UAV Type	Application	Payload (Tank Capacity)	Nozzle Type	Spraying Width (m)	Flight Speed (m/s)	Flying height (m) Above The Crop Canopy	Reference
Rice	Hexacopter Drone	Pesticide	16 L	–	–	5	1.5 - 2m	(31)
Rice	Hy–B–15l (Single Rotor)	Pesticide	15L	Tee Jet 110067	4-5m	5	1.5m	(32)
Rice	Hexacopter Drone	Fertilizer and Pesticide	16 L	–	–	4	2m	(33)
Maize	Battery-Operated	Nutrients	10L	Flood Jet	3.5 m	4–5	0.75 to 1 m	(34)
Maize	Fuel-Operated	Nutrients	16 L	Flood Jet & Atomizer	4m	4–5	0.75 to 1 m	(34)
Cotton	Xag P Series Plant Protection UAV	–	15L	Centrifugal Nozzles	3.5m	–	1-3m	(35)
Cotton		Fertilizer and Pesticide	10L	Centrifugal Nozzles	1.5 – 3m	1-8	2m	(36)
Sugarcane	Quad-Rotor Electric Drone	Pesticide	15L	Centrifugal Nozzles	–	4	3m	(1)
Sugarcane	Single-Rotor Drone	Pesticide		Centrifugal Nozzle	–	2-3	6 (above the ground level)	(1)
Sugarcane	Tiger Drone	Fertilizer	10L	Flat Fan		3-6		(42)
Black Gram	Battery-Operated	Nutrients	10L	Flood Jet	4 m	4-5	1 m	(39)
Black Gram	Fuel-Operated	Nutrients	16 L	Flood Jet & Atomizer	4m	4-5	1 m	(39)
Green gram	Ad610d	Nutrients	10L	Flat Fan Standard Nozzle	3.5m	–	1.5m	(40)
Papaya	Dji T10		10L	XR110015 and MGA015)	3-5.5m	5	2.5m	(40)

below 5 km h^{-1} were optimal conditions for effective pesticide spraying (31). Similarly, research carried out in the rice fields of China explored miniaturized UAVs for efficient pesticide spray without crop damage. Standardized parameters (1.5m height, 5m/s speed) ensured effective delivery and uniform distribution (CV = 23%), yielding high insecticidal efficacy (92-74%). UAV spraying surpassed conventional methods, enhancing pesticide activity duration (32). Another experiment was conducted to standardize the fertilizer and pesticide spraying in a paddy field in Parit Keladi Village, Indonesia. Impact assessments on paddy growth, including leaf length and tiller number, were carried out. The drone achieved ground coverage of 6-7.5 m at a 4 m altitude, equipped with four nozzles and a 1.6 l m^{-1} spraying flow rate. This study introduced drone technology to conventional paddy fields, which is significant in Indonesia and other Asian countries (33). Hence, these experiments ensure optimal drone functions such as effective pesticide delivery, fertilizer application and better crop production.

Maize

Maize is also one of the important staple crops in the world. Agricultural Research Station of the Tamil Nadu Agricultural University situated at Bhavanisagar, Tamil Nadu, India, conducted a study on delivering nutrients to maize via foliar spray using battery-operated and fuel-operated drones with the traditional knapsack hand sprayer. They utilized battery-operated and fuel-operated drones with specific parameters. A battery-operated drone features a 10-litre tank and a 16000 mAh battery, with a spraying width of 3.5 meters and a flying height of 0.75 to 1 meter above the crop canopy. The fuel-operated drone has a 16-litre tank and a 4-litre fuel tank, with a spraying width of 4 meters and a flying height of 0.75 to 1 meter above the crop canopy. UAV spraying surpassed conventional methods and enhanced biometric attributes. The benefits of drone spraying include reducing the amount and expenses of nutrients, lower cost compared to traditional spraying techniques and significantly decreased spray fluid necessity (34).

Cotton

Cotton is an important commercial crop and to ensure improved penetration and uniform distribution of applied chemicals, UAV spraying requires optimizing flight height, spray volume and droplet size. In Xinjiang, experiments were conducted and the parameters selected include spray volume (8.7, 12 and 15 L/ha in 2018; 18, 22.5 and 30 L/ha in 2019), droplet size (100, 150 and 200 µm in both years) and flight height (1, 2 and 3 m in 2018 only). The study found that adjusting flight height, spray volume and droplet size notably affects spray penetration. Lowering drone flight height, increasing spray volume and enlarging droplet size enhance droplet distribution at the lower cotton canopy. However, flight parameters minimally affect droplet distribution uniformity (35). Understanding droplet distribution, drift and cotton aphid and spider mite control effectiveness and cotton leaf adhesion and absorption in UAV spraying. Droplets were collected using Kromekote card and filter paper and parameters such as droplet density, coverage rate, deposition and drift percentage were statistically examined. The combined results showed that at a UAV flight altitude of 2 meters, droplet uniformity, coverage rate, deposition and drift ability increased (31).

Sugarcane

The ideal spraying parameters for sugarcane crops were a spray volume of 15 L/ha, a flight height of 3 m and a flight velocity of 4 m/s (1). The most effective spraying parameters identified were a flight height of 6.0 m and a flight velocity of 2.5 m/s, resulting in a minimal pesticide usage of 15.38 L/ha. These findings explain the appropriate parameters for single-rotor drone applications in sugarcane protection (37).

Pulses

Agricultural Research Station, Tamil Nadu Agricultural University located at Bhavanisagar, Tamil Nadu, India, experimented with applying nutrients to black gram via foliar spray using battery-operated and fuel-operated drones with the traditional knapsack hand sprayer. (35, 38) utilized battery-operated and fuel-operated drones with specific parameters. A battery-operated drone features a 10-litre tank and a 16000 mAh battery, with a spraying width of 4 meters and a flying height of 1 meter above the crop canopy. The fuel-operated drone has a 16-litre tank and a 4-litre fuel tank, with a spraying width of 4 meters and a flying height of 1 meter above the crop canopy. Drone spraying showed greater efficiency than manual knapsack sprayers (39). While in Green gram, Anbil Dharmalingam Agricultural College and Research Institute, in Tiruchirappalli, India, conducted a study to assess the viability of utilizing drones for foliar nutrient spraying on the growth characteristics, yield and economic aspects of green gram cultivation. It used drones with specific parameters, including a tank capacity (Litres) of 10, a Spraying width (m) of 3.5 and a Flight height (m) of 1.5(40).

Papaya

To assess the effectiveness of droplet distribution utilizing an unmanned aerial vehicle across various application rates (12.0, 15.0 and 18.0 L/ha) and spray nozzles (XR110015 and MGA015) targeting different layers (upper, middle and lower) and papaya fruit clusters. They utilized a DJI T10 drone with specific parameters, including a payload of 10L, a Spraying width (m) of 3 -5.5, a Flight height of 2.5 meters above the crop canopy and a flight speed of 5.0 m/s (41). Thus, the results of these experiments help standardize the protocols and operating procedures for drone application among different crops, which could increase and improve crop productivity.

Prospects of Drone Technology

Advanced data analytics and technology are coupled to optimize the resources and agronomic practices encompass the potential of drones as a critical facet in Sustainable agricultural systems (43). The increasing accessibility of drone technology is enabling its integration into precision agriculture practices (44) (Fig. 2). In precision agriculture (PA), drones are utilized to efficiently monitor various stages of crop growth, facilitating the collection and processing of extensive data about crop health across different developmental stages (45). Precision agriculture utilizes multiple technologies, including the global positioning system, geographic information system, remote sensing (RS), sensors and data analysis, to gather information on crop conditions and soil diversity. Subsequently, this data can be employed to make well-informed decisions regarding applying inputs such as water, fertilizer and pesticides (43). UAVs are frequently used in agriculture to conduct RS tasks, such as surveying crop fields and overseeing livestock (38). Specifically, UAVs equipped with multispectral cameras have proven valuable in assessing crop yields, tracking crop height, mapping weed distribution and monitoring biomass. Additionally, using UAVs with high-resolution cameras and various sensors allows for observing topographic alterations within watersheds (46).

These surveys provide precise coordinates of contaminations, which can be integrated into water quality monitoring plans for additional sampling. In addition to RS, UAVs and specialized sub-systems can be employed for on-site measurements of water quality parameters such as pH, dissolved oxygen, electrical conductivity and temperature in surface waters (47). Complementing on-site measurements using tailor-made water collection devices can enhance water sample collection, thereby improving water quality monitoring in larger water bodies. Precision agriculture applications using UAVs cover a wide range of tasks, including crop health monitoring, pesticide and fertilizer spraying, vegetation growth monitoring for yield estimation, vegetation health monitoring and pest management, irrigation management, water stress assessment, nutrient status monitoring as well as deficiency, evapotranspiration (ET) estimation and weed control.

Crop Monitoring and Management

In precision agriculture, drones are instrumental in field mapping and crop condition monitoring, as depicted in Fig. 3(2). Equipped with a diverse array of advanced sensors, including multispectral and thermal cameras, drones facilitate the collection of remote sensing data, enabling comprehensive observation of crops. Analysis of this data allows for evaluating crop health, detecting diseases or pests and tracking overall plant growth. Leveraging

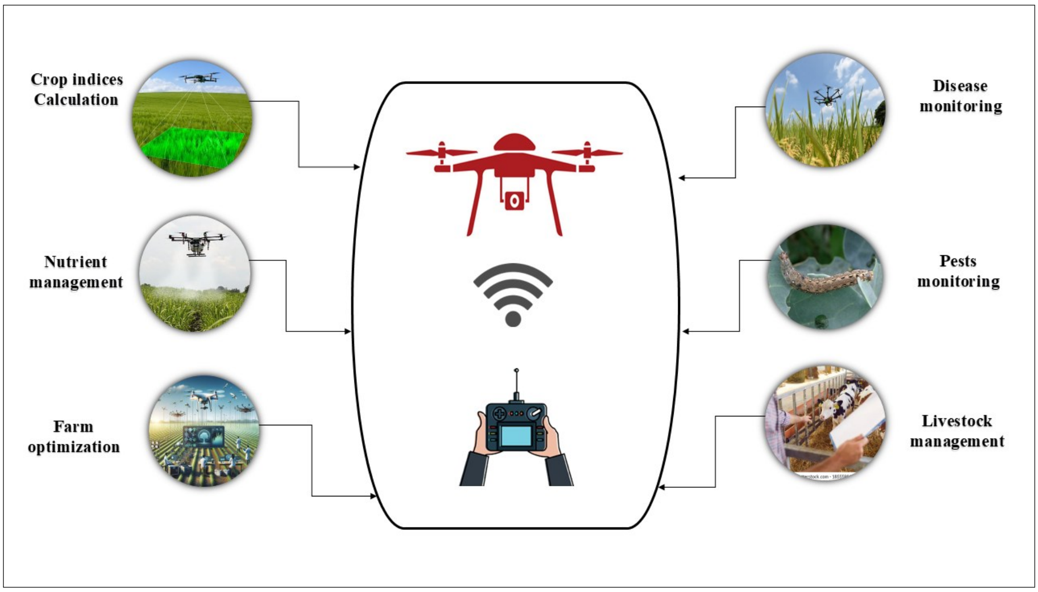

Fig. 2. Application of drone technology in precision agriculture.

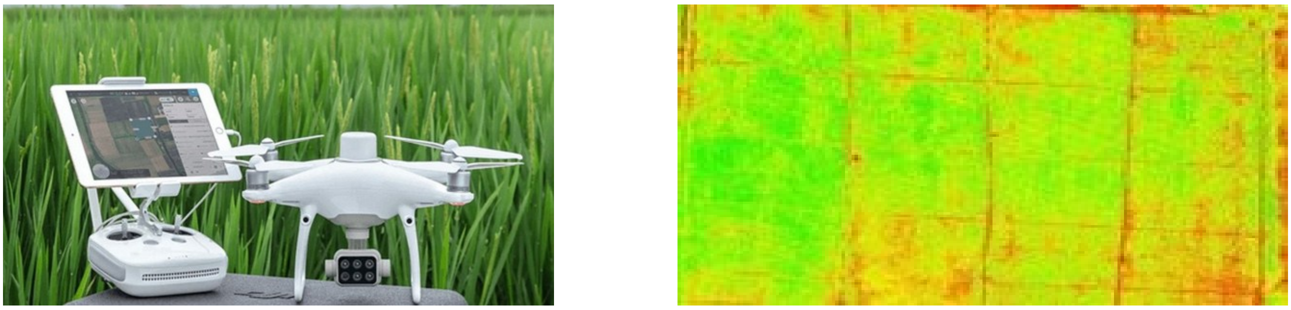

Fig. 3. DJI P4 multispectral drone and vegetative indices (NDVI) (54).

drones for crop monitoring and cutting-edge management empowers farmers to make data-driven decisions regarding irrigation, fertilization and pest management (9). Drones equipped with various sensors, including those for visible, near-infrared (NIR) and thermal infrared wavelengths, enable continuous monitoring of crops throughout the growing season. These drones can assess crop conditions, including water stress, nutrient deficiencies, pest infestations and diseases, by computing multispectral indices derived from reflection patterns. Even before visible symptoms manifest, early detection facilitates timely intervention and serves as an early warning system for effective remedial actions (48). UAVs can survey extensive hectares of fields in a single flight. Thermal and multispectral cameras are mounted on the underside of the quadcopter to capture observations, recording the reflectance of the vegetation canopy (49). The camera captures one image per second, storing it in onboard memory before transmitting it to the ground station via telemetry (9).

A UAV-based monitoring system addresses precision management in crop production (50). The UAV crop–growth monitoring system comprises three primary components: the UAV platform, the crop-growth sensor affixed to the UAV and the ground-based data processor (9). The crop-growth sensor, mounted on the UAV platform, records real-time reflection spectra from the crop canopy. Subsequently, the ground-based data processor wirelessly receives and processes this data. By estimating indices such as NDVI, RVI, LNA, LAI and LDW and providing critical insights into crop growth, the processor contributes to the crop growth and health-monitoring model (51). These technological advancements will give farmers more precise and comprehensive information about their crops, leading to increased yields, reduced input costs and enhanced farm profitability (52).

Nutrient and Deficiency Monitoring

In agriculture, ensuring plants receive optimal nutrient levels is crucial for achieving robust growth and maximizing yields. Essential nutrients such as nitrogen, phosphorus and potassium play distinct roles; nitrogen promotes leaf growth, phosphorus supports root and stem strength and potassium enhances disease resistance. The NDVI aids in identifying areas of crop stress, enabling targeted intervention (53). UAVs equipped with near-infrared (NIR) and multispectral imagery facilitate early detection of management zones, allowing proactive measures before visible symptoms manifest. Currently, nutritional assessments often rely on subjective visual inspections or labour -intensive laboratory leaf analyses, both of which have limitations in accuracy and efficiency (55). Alternative methods, such as the chlorophyll meter (SPAD), provide indirect estimates, albeit with drawbacks, including time consumption and potential inaccuracies (56-58). Consequently, there is a growing emphasis on exploring novel approaches for identifying and quantifying plant nutritional deficiencies (46). Many studies in the literature derive vegetation indices (VI) from imagery and establish correlations with nutrient content through regression models, often employing linear models. However, less prevalent, other categories of variables have also been incorporated into regression models, such as the spectra of average reflectance selected spectral bands, colour features and principal components (47,59-61).

Site-Specific Nutrient Management

Applying fertilizers and chemicals is crucial for crop health and yield optimization in agriculture. Drones have revolutionized precision agriculture through specialized applications such as spraying (62). With advanced capabilities like GPS, autonomous flight control, real-time image transmission and various sensors, UAVs efficiently gather high-resolution spatial data for rapid analysis. They can perform regular surveillance and monitor abnormal conditions (63). Drones can deliver chemicals such as fertilizers and pesticides, adjusting quantities based on spatial crop variability and pest severity. Integrating UAVs with sprayer systems supports accurate, site-specific application in extensive crop fields, necessitating heavy-lift UAVs for larger spraying areas (64). The lightweight and inexpensive Quadcopter (QC) system, also referred to as a UAV, was proposed by researchers (65). Researchers have proposed lightweight and cost-effective quadcopter (QC) systems for indoor and outdoor crop spraying, autonomously controlled via Android devices. Leveraging machine learning algorithms ensures precise identification and treatment of insect pests, enabling targeted interventions without compromising healthy crops (62). These drones reduce the need for pesticides and minimize environmental impact, offering improved efficiency and cost-effectiveness compared to conventional spraying methods (66).

Utilizing drones for precise interventions allows farmers to apply fertilizers, pesticides and herbicides with exceptional accuracy. This targeted approach minimizes chemicals, leading to cost savings and a reduced environmental footprint compared to conventional widespread spraying methods (4). Moreover, drones can be automated to fly independently over designated regions, pinpointing areas of interest by assessing crop health factors like moisture, nutrition and pest presence. The data gathered offers crucial insights for proactive crop management, empowering farmers with enhanced control and understanding and fostering sustainable and efficient agricultural practices (9). Advancements in technology have introduced drones to agriculture, offering an innovative and efficient method to reduce chemical usage and promote smart farming, minimizing potential environmental impacts (67). Reducing chemical dependency in agriculture is just one of the advantages of drone technology; it also facilitates enhanced crop monitoring, early pest and disease identification and efficient land mapping for improved resource management (2). Incorporating drone technology into agriculture reduces reliance on chemicals and advocates for sustainable and resource-efficient farming methods, ultimately yielding positive environmental outcomes (68).

Water Conservation and Soil Health

Multiple factors contribute to water stress in crops, and characterizing this stress can be difficult (61). Derived variables from thermal images often depend on subtle temperature fluctuations to identify stresses and other phenomena. Consequently, thresholds and regression equations established under specific conditions typically do not apply under even slightly different circumstances. Scientists employed a variety of sensors and modelling techniques to assess instances of water stress. Drones fitted with specialized sensors can calculate these indices, which could help monitor water stress. Using multispectral hyperspectral or thermal infrared imagery, vegetation indices (NDVI, GNDVI, etc.), the difference between the canopy, air temperatures (Tc - Ta) and canopy temperature directly (69), crop water stress index (CWSI) can be calculated.

Drones are also instrumental in monitoring soil health, capturing detailed images and data to evaluate erosion, compaction and nutrient levels. Utilizing drone-supplied data for decision-making allows farmers to improve soil fertility and overall health, promoting sustainable long-term growth (70). Additionally, drones facilitate the acquisition of valuable data and insights, enabling farmers to make informed decisions regarding soil management strategies, ultimately enhancing soil health and productivity (71).

Evapotranspiration (ET) estimation

Evapotranspiration (ET) is a vital process that involves water transfer from the land to the atmosphere through soil evaporation and plant transpiration. With careful concerns about water scarcity, population growth and climate change, evapotranspiration estimation has become a significant focus in agricultural research. Estimates show that different types of UAVs have various functions in evapotranspiration. Fixed-wing UAVs are ideal for large-scale fields because of their two-hour average flying time. In contrast, quadcopters are used for quick missions in smaller fields because of their shorter flying duration of around 30 minutes (69). UAVs introduce new research challenges when utilized as remote sensing platforms, including drone image processing and flight path planning. An example includes using a fixed-wing UAV to gather thermal data for estimating ET through two-source energy balance models (12). Unmanned aerial vehicles (UAVs) can reduce these temporal and spatial constraints. The UAVs can be equipped with lightweight sensors and cameras to capture high-resolution pictures. The spatial resolution of UAV photographs can reach the centimetre level compared to satellite imagery.

Additionally, UAVs can fly whenever needed, allowing for high-temporal images. So, various UAV-based techniques are used for evapotranspiration (72). Utah State University developed an airborne digital system to gather multispectral and thermal images for evapotranspiration estimation (73). These cameras have the following spectral bands: Near-infrared (NIR) (0.780µm-0.820 µm), Blue (0.465µm-0.475µm), Green (0.545µm-0.555µm) and Red (0.645µm-0.655µm). UAV platforms with lightweight sensors can give higher quality and spatial and temporal resolution images compared to other satellite-based remote sensing techniques (72).

Decision-Making System for Farm Optimization

Agricultural remote sensing proves highly beneficial by enabling the comprehensive observation of crops on a broad scale, employing a synoptic, remote and non-invasive approach. Typically, this technology employs sensors mounted on UAVs to capture the reflected or emitted electromagnetic radiation from plants (74). The collected data is then processed to generate valuable insights and products. These insights encompass various characteristics of the agricultural system, showcasing their spatial and temporal variations. Functional traits refer to the biochemical, morphological, phenological, physiological, and structural features that govern the performance or fitness of organisms, particularly plants (74). Plant traits, categorized as typological, biological, physical, structural, geometrical, or chemical, exhibit variations across plant species and locations. Remote sensing (RS) establishes a crucial link with traits such as leaf area index, chlorophyll content and soil moisture (75). Accurate interpretation relies on crop phenology, type, soil characteristics, weather, etc.

Remote sensing yields key information products like plant density, leaf biochemical content and soil moisture, aiding in assessing crop health, disease, irrigation timing, nutrient status and yield predictions. This data is crucial for interpreting crop health, disease incidence, irrigation needs, nutrient deficiencies and generating predictions (74). With the global population on the rise, frequent shifts in climate patterns, and limited resources, meeting the food demands of the current population has become a formidable challenge (76). Precision agriculture, also called smart farming, has emerged as an innovative solution to address the sustainability issues in agriculture. Integrating drone technology in precision agriculture facilitates sophisticated analytics and data-centric decision-making, leading to optimized farm operations (77). This acquired knowledge enables farmers to make well-informed decisions regarding irrigation schedules, nutrient management and pest control, ultimately enhancing productivity and minimizing waste. Additionally, the application of advanced analytics aids in identifying trends and patterns within the collected data, empowering proactive and timely interventions to mitigate risks and maximize crop yields (78).

Crop Protection

Data-driven disease detection

Crop diseases, whether fungal, bacterial, or viral, threaten agricultural productivity. Timely detection enables proactive measures such as removing infected plants to prevent spread. Image-based tools are instrumental, especially when manual assessment is impractical, unreliable, or inaccessible, with UAVs enhancing surveillance capabilities (79). RGB and multispectral images have traditionally been utilized, with ongoing exploration into hyperspectral and thermal imagery (80, 81). Thermal imaging, in particular, aids in detecting water stress induced by specific diseases. UAVs equipped with infrared cameras offer detailed insights into plant internal structures (82), precisely capturing various data types such as visual, thermal and infrared. Integrating this data into analytics platforms facilitates actionable insights and predictive capabilities, supporting sustainable decision-making (83).

Pest surveillance and management

The combination of a sprayer system mounted on a UAV for pesticide spraying presents a promising opportunity for effective pest management and vector control. This integrated solution offers precise site-specific application, particularly beneficial for extensive crop fields. Heavy-lift UAVs become essential for spraying operations to cover large areas efficiently (64). The spraying drone has various components (Fig. 4) and drones with an integrated spraying system flow chart are displayed in Fig. 5. The effectiveness of the spraying system, when attached to the UAV, is enhanced by the use of a PWM (Pulse Width Modulation) controller in pesticide applications. (84). A prototype is designed to create a UAV capable of adjusting the mean diameter droplet size up to 300mm. The growing popularity of UAVs in spraying operations is attributed to their speed and precision (85). On the contrary, crop quality may be compromised due to issues such as inadequate coverage during spraying, overlapping in crop areas and ineffective treatment of the outer edges of the field. To address these challenges, a control loop algorithm was implemented in agriculture operations, employing a swarm of UAVs to handle the precise spraying of pesticides (86). These unmanned aerial vehicles take responsibility for overcoming the mentioned factors and ensuring more effective and uniform pesticide application across the entire crop field.

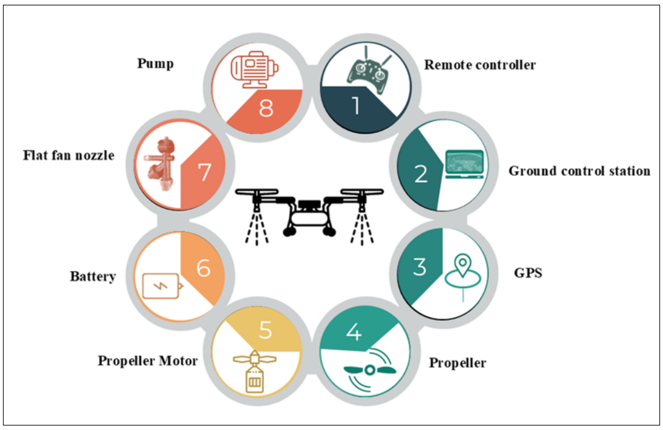

Fig. 4. Components of spraying drone.

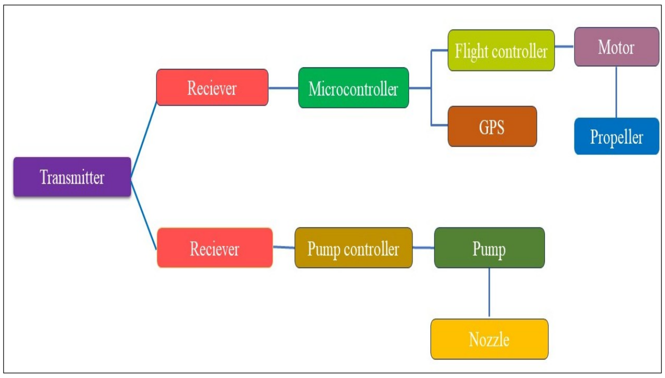

Fig. 5. Flow chart of UAVs for pesticide application.

Weed control

Undesirable plants, or weeds, pose crop challenges by competing for resources, potentially reducing yields. Herbicides are commonly used in conventional farming, but their excessive application may lead to herbicide-resistant weeds, impacting crop growth. Employing hyperspectral images to distinguish between weed spectral signatures with varying glyphosate resistances is explored (87). RGB sensors categorize different types of weeds (85). Researchers utilized drones equipped with hyperspectral sensors to track weeds based on leaf density and chlorophyll in the plant canopy (88). Moreover, it presents a significant environmental pollution risk. Site-specific weed management relies on accurate weed cover maps for precise herbicide spraying to address these issues. Drones capture field images to create such maps. Utilizing drones for herbicide spraying proves effective for pre- and post-emergence weed control. It allows spraying in diverse fields, including mud, weeds, and various weather conditions. The drone application ensures efficient weedicide use and is user-friendly, portable and easy to maintain (69).

Livestock monitoring

In livestock monitoring, drones offer numerous applications for animal husbandry and prove valuable for overseeing extensive herds. Animals on the farm are fitted with sensors or radio-frequency identification (RFID) tags, enabling tracking of their feeding patterns and movements. Drones monitor livestock more frequently, accomplishing this quickly without extensive personnel involvement (89). The concept of remote-sensing fencing or virtual boundaries involves creating a virtual obstacle or security barrier within a specified spatial area, which is particularly useful in the context of free-range livestock grazing. Equipped with high-resolution infrared cameras, these drones can promptly identify diseased animals based on their heat signatures. Once a diseased animal is detected, it can be isolated from the rest of the herd, allowing for early intervention and treatment. This application positions drones as a tool for precise dairy farming (90).

Challenges in Drone Technology for Sustainable Agriculture

Every technology encounter initial limitation and drones are no exception. Drones in sustainable agriculture face challenges such as limited battery life, connectivity issues in remote areas and regulatory hurdles. These issues can impact efficiency and effectiveness, but ongoing research aims to overcome these obstacles and maximize drone potential.

Limited battery life

The main limitation of UAVs is their maximum flying time is limited by the energy provided by batteries when drones cover large areas or lengthy flights for data collection purposes this limitation can cause difficulties (91). One main constraint concerns technological capabilities, particularly battery life and flight duration (Table 3). Currently, the market has a maximum operating duration of approximately thirty minutes, due in large part to constraints in battery capacity and weight (92). This constraint significantly reduces the area coverage of drones that can be used for spraying, monitoring and surveying.

Table 3. Battery life and flight duration factors affecting flight duration for different types of agricultural drones

Drone Type	Average Battery Life	Range of Flight Duration	Factors Affecting Flight Duration	Reference
Multi-rotor drones	20-30 min	15-45 min	Size, weight, motor power, payload weight, weather	(93)
Fixed-wing drones	30-60 min	20-90 min	Size, battery capacity, motor efficiency, spraying rate, wind	(94)
Vertical Take-Off and Landing (VTOL) drones	25-40 min	18-50 min	Motor type, payload weight, spraying intensity, flying speed	(95)
Hybrid drones	30-45 min	20-60 min	Battery capacity, hybrid propulsion efficiency, payload weight, flight distance	(96)

Cost scalability

The expense of buying and maintaining agricultural drones is a hurdle for farmers (97). The operational cost is also very high, it includes batteries, sensors and other equipment that are necessities for operations and may need to be upgraded or replaced regularly. Moreover, there are expenses related to operator training and following rules (98).

Data analysis and interpretation

Another significant constraint is data analysis. Drones equipped with hyperspectral sensors often generate many terabytes of data, requiring proper storage, specialized software for processing and analysis by experts with years of experience. As a result, there is a significant delay between data collection and obtaining results. While multispectral data processing is significantly faster than hyperspectral data processing, accuracy is very low (99). The remote and rural settings of many farms introduce challenges related to connectivity and the real-time processing of intricate sensor data collected by drones (100). Agriculture drones collect massive amounts of data, making Data Analysis and Interpretation challenging and time-consuming to handle and analyze (96).

Adverse weather conditions

The unfavourable weather conditions could restrict the sensing and response of drone activity (101). Additionally, weather conditions like heavy winds or precipitation pose operational difficulties for drones, particularly those with lighter structures. In general, drone flight missions are designed in such a way as to minimize the constraints as mentioned earlier. Responding to the constraints occurring under unfavourable conditions may require atmospheric, radiometric and geometric corrections, which may require accurate data collection and processing, which are usually application-specific.

Atmospheric correction

The sun emits electromagnetic energy (EM) toward the earth, but before it reaches the surface, some is absorbed and dispersed by dust and gases in the atmosphere. Aerial imagery for surface reflectance observations is influenced by various processes related to the propagation of electromagnetic radiation within the atmosphere-surface system. Under clear sky conditions, the relevant processes include gaseous absorption, molecular scattering, aerosol scattering, absorption and water surface reflection. In cloudy conditions, cloud droplet scattering makes surface sensing challenging, with the cloud signal predominantly prevailing. An exception arises when clouds are optically thin or cover only a tiny portion of the pixel, meaning their impact on pixel reflectance is less than 0.2 (102).

The quality of information derived from aerial image measurements, including vegetation indices, is affected by atmospheric effects. Errors induced by atmospheric effects can potentially elevate uncertainty by up to 10%, varying depending on the spectral channel (63). Moreover, much of the signal an imagery sensor receives from a dark object, like an area experiencing water stress, is attributable to the atmosphere at visible wavelengths, assuming that near-infrared and middle-infrared image data are unaffected by atmospheric scattering effects. Consequently, pixels from dark targets indicate the amount of upwelling path radiance in that band. The influence of the atmosphere and surface must be eliminated to access accurate surface reflectance. This necessitates an atmospheric correction model, particularly when vegetation indices (103) are utilized in vegetation monitoring and dark scenes where atmospheric scatters can mask features like water stress and drought. Atmospheric correction removes atmospheric effects, variable solar illumination, sensor viewing geometry and terrain influence on image reflectance values, thereby determining their actual values. Supplying, calibrating and adjusting for atmospheric conditions at the time of imaging are crucial atmospheric correction prerequisites.

Radiometric correction

Radiometric calibration establishes the functional relationship between incoming radiation and sensor output, such as digital number (104). Accurate radiometric calibration is essential for change detection and interpretation, especially when images are captured at different dates, times, locations or by other sensors. It ensures that changes in the data reflect actual field changes rather than variations in the image acquisition process or conditions (e.g., changes in light intensity). Many image collections involving hyperspectral cameras (e.g., crop phenotyping, disease detection and yield monitoring) necessitate precise radiometric calibrations.

Several potential solutions can mitigate radiometric variation. Light intensity fluctuates over time due to changes in solar elevation, atmospheric transmittance and cloud cover. Therefore, conducting image collection flights during periods of minimal solar elevation could reduce radiometric variation in collected data. Additionally, manually or automatically, digital camera exposure settings should be carefully chosen based on overall light intensity (105).

Geometric correction

Unmanned Aerial Vehicles (UAVs) capture imagery for aerial mapping of agricultural landscapes. Still, this data often contains geometric distortions arising from various factors such as sensor position variations, platform motion and earth's rotation. These distortions, categorized as internal and external factors, lead to inconsistencies in pixel size and inaccurate geographic coordinates of image pixels. Geometric correction is essential to rectify these distortions and ensure the accurate representation of features in the corrected image (106). By calibrating intrinsic camera parameters like focal distance and lens distortion, geometric correction restores the geometric integrity of the image, facilitating precise spatial analysis.

Regulatory and legal hurdles

A significant challenge in integrating drones for precision agriculture is ensuring compliance with the diverse regulatory requirements that govern the use of UAVs in various geographic areas (Table 4). Depending on the geographical location, drones might necessitate registration, licensing, certification, insurance, or permission to operate within specific airspace or over designated land (107). Moreover, drone pilots need to follow regulations regarding safety, privacy, security and environmental concerns linked with their drone operations. These rules may differ depending on factors such as the type, size, weight, speed, altitude and intended use of the drone, emphasizing the necessity for operators to be knowledgeable about and adhere to the relevant legal stipulations and limitations applicable to their drone usage and geographic location (108).

Despite drones being utilized in agriculture for the past two decades, regulations about their use in agricultural settings are still nascent worldwide. Although India's utilization of drones in agriculture lags that of the US and China, New Delhi has taken proactive measures to establish regulatory frameworks for global drone governance. This initiative is partly driven by the recognition of the potential security implications of drone technology for India and the strategic advantage of leading in this domain to safeguard national interests. At the international level, the International Civil Aviation Organization (ICAO) plays a pivotal role in developing rules and regulations for drone operations, with its initial efforts dating back to 2007. However, it was not until 2011 that the ICAO issued its first set of rules in Circular 328. In December 2018, the Indian government introduced a drone policy facilitating drone applications, particularly for agriculture.

The DGCA and GOI regulations implicitly permit using RPAS, i.e., Drone/ UAV, for agricultural purposes except for spraying pesticides until specifically cleared. The DGCA RPAS Guidance Manual provides procedures for the issue of Unique Identification Numbers (55). Unmanned Aircraft Operator Permits (UAOP) and related activities by drone regulations are restricted in various designated areas, including densely populated zones, near airports, during poor weather and around sensitive facilities. Operators above 18 must maintain a visual line of sight, possess a valid license plate and insurance and refrain from exceeding altitude limits or flying multiple drones simultaneously. Addressing regulation, ethics and implementation issues is imperative, necessitating alignment with existing legal and moral principles and adaptation to rapid technological advancements to establish an effective governance framework for UAVs in India (109).

Agricultural drones make precision farming and resource optimization possible, yet there are drawbacks related to data processing, cost scalability and regulatory compliance. By overcoming these obstacles, drones in various fields will reach their full potential (97).

Future Direction

In the realm of agricultural technology, drone technology stands out for its efficiency and adaptability across various operations. However, for small-scale farmers, the high cost of purchasing and maintaining agricultural drones poses a significant challenge. The wider adoption and accessibility of drones depend on their scalability and affordability, including the equipment and training and support services. Despite this, the high initial investment costs and the need for policy reforms remain major hurdles in making drones more accessible to farmers. Additionally, there is a pressing need for comprehensive research to optimize operational protocols and validate the effectiveness of drone applications. One critical area of investigation involves understanding how drone-induced airflow affects liquid distribution during spraying. Recent studies have shown a correlation between the rotational speed of drone rotors and the deposition of liquid droplets on plant surfaces. Interestingly, higher rotor speeds reduce liquid deposition on lower plant levels, suggesting that airflow generated by the rotors can alter distribution patterns. As a result, the uniformity and efficacy of pesticide application remain uncertain, highlighting the need for further research to refine these processes. Beyond these challenges, numerous unresolved issues persist, making ongoing research essential for enhancing the efficiency and effectiveness of drone technology in agriculture. Addressing these limitations is key to realizing the full potential of drones in improving agricultural practices.

Table 4. Regulatory and legal hurdles

Challenge	Description	Impact	Reference
Complex permitting processes	Obtaining permits for airspace usage, data collection, and pesticide spraying can be time-consuming and expensive.	Discourages adoption, particularly for small-scale farmers.	(110)
Unclear data ownership and privacy	Lack of clarity on data ownership and privacy raises concerns about farmers' data being used without their consent.	Farmers hesitate to share sensitive data, hindering its potential for analysis and improvement.	(111)
Limited liability and insurance frameworks	Existing frameworks might not adequately address agricultural applications like spraying or livestock monitoring.	Creates uncertainty for farmers and service providers in case of accidents.	(112)
Variable regulations across borders	Differing regulations in different countries create challenges for cross-border operations and data sharing.	Hinders global collaboration and technology advancement.	(110)
Evolving technology and policy gaps	The rapid evolution of drone technology often outpaces regulatory frameworks.	This leads to hesitant adoption by farmers and discourages innovation by developers.	(113)

Conclusion

Drone technology holds immense potential for transforming agricultural practices, fostering sustainability and boosting its efficiency. Its adoption enables the farming community to contribute to global environmental conservation and economic resilience efforts. Drones' versatile applications, such as crop health monitoring, precision spraying, data-driven decision-making and soil health assessment, align with Sustainable Development Goal (SDG) 2, aiming for Zero Hunger. Moreover, drone use in precision agriculture significantly supports SDG 13 (Climate Action) by reducing greenhouse gas emissions linked to conventional farming. Nonetheless, several challenges impede the widespread adoption of drone technology. Issues such as short battery life and operational limitations during adverse weather conditions present practical barriers that need to be addressed for broader implementation. Regulatory frameworks vary significantly across regions, necessitating adherence to complex guidelines and obtaining permits. This variability, coupled with the high initial cost of drones and the requisite expertise in operation and data analysis, can pose barriers for small-scale farmers.

An Agricultural Drone Subsidy system could play a crucial role in overcoming these challenges, especially in developing countries. Providing financial support, subsidies, or low-interest loans can help smallholder farmers afford drone technology. Governments and international organizations can also direct subsidies toward training programs, ensuring farmers gain the skills to operate drones and interpret data effectively. Continued research and development efforts are essential to unlocking the full potential of drones. Focus areas include improving battery life, enhancing sensor capabilities, and streamlining regulations to increase accessibility. Capacity-building initiatives can further equip farmers with the necessary knowledge to leverage this technology. By addressing these challenges and harnessing the transformative power of drones, agriculture can transition toward a future marked by sustainability and efficiency, ensuring food security. Collaborative approaches involving multiple stakeholders will be instrumental in effectively transferring UAV technology to farmers, making this innovation more accessible at the field level.

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Authors' contributions

RS contributed to the manuscript's conceptualization, literature review and drafting. KP, PS and KR provided critical insights and revisions to improve the scientific rigor of the review. SN, MD and MR were responsible for acquiring and analysing relevant literature. VB and STV contributed to the organization and refinement of the manuscript, ensuring clarity and coherence. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

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