PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–09
https://doi.org/10.14719/pst.5773

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REVIEW ARTICLE

Sky to soil: Role of drones in maximizing agricultural crops yield

Nithiya Ashok AK[1], Muthumanickam D[1]*, Pazhanivelan S[2], Kumaraperumal R[1] & Kannan P[2]

[1]Department of Remote Sensing and Geographic Information System, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Center for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: muthutnausac@gmail.com

OPEN ACCESS

ARTICLE HISTORY
Received: 13 October 2024
Accepted: 10 November 2024
Available online
Version 1.0 : 31 December 2024
Version 2.0 : 23 January 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Nithiya AAK, Muthumanickam D, Pazhanivelan S, Kumaraperumal R, Kannan P. Sky to soil: role of drones in maximizing agricultural crops yield. Plant Science Today.2024;11(sp4):01-09. https:/doi.org/10.14719/pst.5773

Abstract

As agricultural practices aim to boost productivity to meet global food demand, drones have emerged as transformative tools offering aerial intelligence to guide data-driven crop management. Drones are revolutionizing agriculture by their capacity to perform precise tasks related to crop health monitoring, pest and disease detection, spraying, mapping and other related activities. Comparing the advancement with traditional ground techniques such as manual crop scouting, ground-based sprayers and satellite imagery reveals many advantages regarding accessibility, precision, efficiency, safety and sustainability, besides increasing farm productivity. Drones also help to make well-informed decisions by delivering timely, high-quality agricultural data to increase yields. However, significant obstacles, such as battery life restrictions, expertise shortages and problems with data processing, are highlighted. The various applications of drones in optimizing agricultural outcomes, ranging from assessing crop vigour to assisting in pollination, are conferred. Additionally, there is a vast potential for drones to transform farming through precision agriculture, provided that proactive measures are taken to address the limitations. With remote sensing and autonomous capacities improving continually, drones can grant farmers unmatched awareness and control to reduce risks and extract the maximum productivity from finite land resources.

Keywords

Agricultural efficiency; drone technology; resource utilization; Unmanned aerial vehicle; yield estimation.

Introduction

As the space of technology progresses, it has integrated itself into nearly every facet of our daily existence. The agricultural industry stands out among the various sectors that have experienced noteworthy progress. Presently, farmers have adopted the utilization of(UAV) unmanned aerial vehicles to transform and modernize their farming methodologies. Drones, equipped with their unique ability to carry out precise farm management tasks, have the potential to augment crop yield and diminish labour expenses (1). In agriculture, the initial model of UAV was pioneered by Yamaha. The Yamaha RMAX, an unmanned helicopter, was explicitly designed for pest control and crop monitoring in agriculture. Regrettably, Yamaha ceased production of UAVs in 2007 due to the agricultural sectors' shift towards integrated pest management and sustainable practices. This has led to a preference for UAVs that minimize pesticide use, diminishing the RMAXs' market relevance(2). Drones can operate independently by utilizing specialized software that enables the creation of a flight plan and the deployment of the system with Global Positioning System (GPS). Moreover, drones can input various parameters, such as speed, altitude, ROI (Region of Interest), geo-fence and fail-safe modes. The preference for drones over full-size aircraft stems from their significant advantages, including low operational costs, high spatial resolution, fast turnaround capabilities and ease of activation (1). It additionally fulfils an essential function in agricultural landscapes that promote biodiversity, aiding in the surveillance and administration of plant well-being, identifying pests and calculating biomass (3).

They use GPS to navigate and determine their location, sensors to gather information on soil moisture and crop health, communication systems to relay information to users on the ground and remote control systems to direct the flight path. Its battery and propulsion systems control the drones' flying time and range, while software manages its flight direction, data collecting and communication (1). Innovative agriculture technologies solve existing challenges and enhance overall productivity (4). Incorporating UAVs into agricultural practices has wholly transformed conventional techniques employed in monitoring and managing crops, resulting in improved levels of productivity and yield. UAVs offer the advantage of providing up-to-the-minute aerial insights, facilitating informed decision-making based on data and optimizing the allocation of resources (5). Drones can be employed in various agricultural applications, such as irrigation, crop surveillance, soil and field analysis and bird control (6) (Fig.1.)

Fig. 1. Drone.

Drone integration into agriculture has the potential to significantly improve the sector by providing farmers with tools to manage resources more effectively, reduce risk and increase productivity and profitability. While no single technology can completely transform the agricultural industry, integrating drones, AI, sensors and IoT capabilities offers a comprehensive approach that addresses several challenges in precision agriculture, including crop spraying, crop health assessments and animal monitoring (7). The aim of this manuscript is to explore the role of drones in modernizing agricultural practices and addressing key challenges in crop management. By integrating advanced technologies such as AI, sensors and IoT, drones offer a data-driven approach to precision farming. This manuscript highlights the potential of drones to optimize resource use, increase productivity and enhance sustainability while identifying the limitations and prospects of drone technology in agriculture.

Pre-Drone Strategies for Boosting Agricultural Yield

***Crop rotation*:** Agriculture has traditionally employed a practice that has persisted for a considerable period, offering many advantages regarding the enhancement of soil fertility, the regulation of pests and diseases and the management of undesirable vegetation (8). Moreover, crop rotation can considerably diminish the accumulation of soil-based plant pathogens and diseases (9). Crop rotation is not widely used, with cover crops uncommon in some regions despite its benefits. For example, rotating legumes like soybeans or peas with cereals like wheat or corn can improve soil nitrogen levels and reduce pest pressure. Similarly, alternating root crops like potatoes or carrots with leafy greens like lettuce or spinach helps manage soil health. Crop rotation is not yet a widely used technique, with cover crops being uncommon in some regions despite its shown benefits (10).

***Improved crop varieties*:** Selective breeding and genetic enhancement in cultivating crop varieties have substantially boosted crop yields and productivity (11, 12). For example, using hybrid maize and enhanced management techniques in cultivation has resulted in a consistent yield rise. Breeding efforts have been responsible for approximately 50% of this increase(13).

Transgenic rice varieties have been developed to improve grain yield by identifying and manipulating quantitative trait loci (QTLs) associated with grain size and weight. Certain transgenic lines have reported yield increases of up to 15% due to enhanced traits like drought resistance and nutrient uptake (2). Advanced genomic techniques, including CRISPR/Cas9, have enabled precise modifications that enhance disease resistance and stress tolerance, improving crop yields (3).

***Mechanization*:** The mechanical apparatus in the agricultural sector, including tractors, ploughs, seeders and harvesters, has transformed farming methodologies, enhancing effectiveness and productivity (14). Installing electronic control systems in tractors, which have increased working conditions, decreased emissions and improved energy efficiency, has caused this change (15). The early stages of adopting new equipment highlight that mechanization has faced its fair share of obstacles, including technical challenges and the need to reorganize traditional agricultural practices (16). This transition often requires farmers and workers to adjust to new workflows, which can be time-intensive and costly. Yet, overcoming these barriers is crucial for reaping the long-term benefits of mechanization.

***Fertilization and soil management*:** Farmers use a range of fertilizers and soil amendments to improve soil fertility and production, with a concentration of nitrogen, phosphorus and potassium (16). Various studies have emphasized the significance of soil amendments and fertilizers in augmenting soil fertility and productivity. The role of organic amendments produced on farms, specifically leguminous intercropping, in sustaining and improving soil fertility has been stressed (17). The advantages of integrated nutrient management, which combines organic and inorganic fertilizers, enhance crop yield and soil fertility (18).

Organic fertilizers, including manure and compost, significantly enhance soil organic matter, nutrient uptake and microbial activity, improving soil structure and fertility. Despite the benefits, reliance on chemical fertilizers can lead to soil degradation and reduced organic matter. Therefore, a balanced approach incorporating organic amendments is essential for maintaining soil health and ensuring long-term agricultural productivity (4). Long-term studies indicate that combining organic materials with inorganic fertilizers can sustain crop yields and improve soil fertility indices over time. Integrated nutrient management, which blends organic and inorganic fertilizers, has increased crop yield sustainability. For instance, the combination of NPK with manure resulted in higher sustainable yield indices in maize-wheat systems(5)

***Irrigation*:** Modern irrigation methods have been adopted to overcome water constraints and seasonal rainfall patterns in agriculture, including drip irrigation, sprinkler systems and furrow irrigation (6). These innovations have made it possible to use water more effectively without compromising agricultural production. Education, the scale of the farm, on-farm demonstrations and legislative subsidies are some factors affecting the adoption of these technologies (19). Implementing water-saving irrigation technology and alternate cropping and irrigation methods in semiarid areas, such as intercropping, can reduce water shortages (20).

Unmanned Aerial Vehicles in Agriculture

A drone, known as unmanned aircraft in technological terminology, is formally referred to as an unmanned aerial vehicle (UAV) or an unmanned aircraft system (UAS). It is defined as dynamic remote-controlled navigation equipment. A drone is a robotic flying entity that can be operated remotely or autonomously to follow pre-programmed flight paths through software-controlled systems embedded within it while simultaneously utilizing onboard sensors and GPS for navigation (21) (Fig. 2.)

Fig. 2. Drone spraying in crop.

Drones are essential to precision agriculture because they capture high-resolution, real-time data, which helps farmers make decisions about insect control, fertilization and irrigation (22). They help minimize waste and maximize resource usage by helping with precise spraying and agricultural input applications (23). Drones map and survey agricultural lands, making crop planning and resource allocation easier (24). It has a particular significance in precision agriculture as it offers the advantage of capturing high-resolution images that can be harnessed for informed decision-making (25). Drones can streamline and enhance monitoring and management activities within the orchard management domain, resulting in resource utilization and better income (26).

UAV Monitoring System: UAVs are a specific aircraft category capable of executing flight operations independently without a human pilot. An operator remotely manages the movement of these aircraft. Within the UAV framework, sensors and cameras capture and transmit visual data to the operator (27). It provides a UAV delivery monitoring system with real-time control, autonomous flying and delivery order assignments. These studies demonstrate that UAV monitoring systems may improve delivery, safety and data collection processes (28) (Fig. 3.)

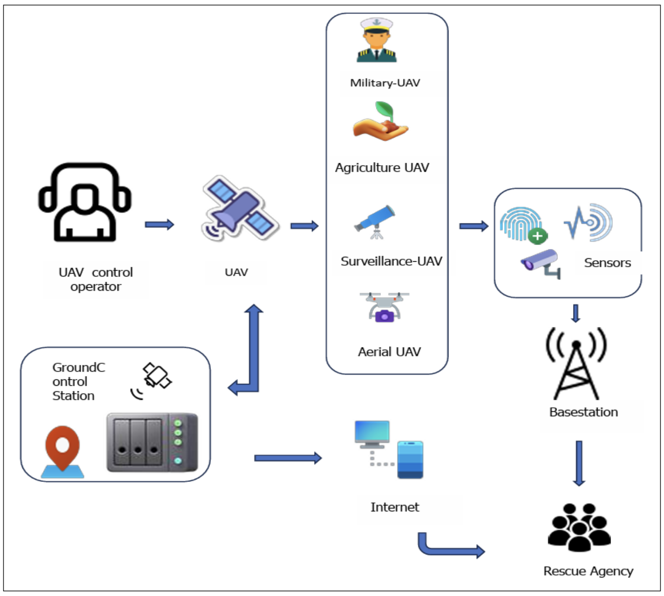

Fig. 3. UAV monitoring system.

Drone Applications in Enhancing Agricultural Yields

***Crop health monitoring* :** UAVs with advanced imaging sensors provide real-time data about crop health and growth patterns (Fig . 4). In China, UAS primarily focuses on enhancing crop production efficiency and minimizing environmental damage, particularly plant protection (29). Drones have significantly transformed agricultural management by furnishing accurate, real-time information about crop health and soil conditions (30). Utilizing UAVs equipped with multispectral cameras in precision agriculture has been a transformative factor, presenting high-resolution imagery for evaluating crop health (31). These UAVs offer unparalleled spectral, spatial and temporal resolution capabilities, enabling their utilization in various applications such as detecting drought stress, weeds and pathogens, assessing nutrient status and predicting yield (32). For instance, UAVs equipped with multispectral sensors have been used to predict maize yield by assessing leaf area index (LAI) and chlorophyll content. The study found that the Wide Dynamic Range Vegetation Index (WDRVI) and the Atmospherically Resistant Vegetation Index (ARVI) were effective in correlating with yield metrics during different seasons(7). Research has highlighted

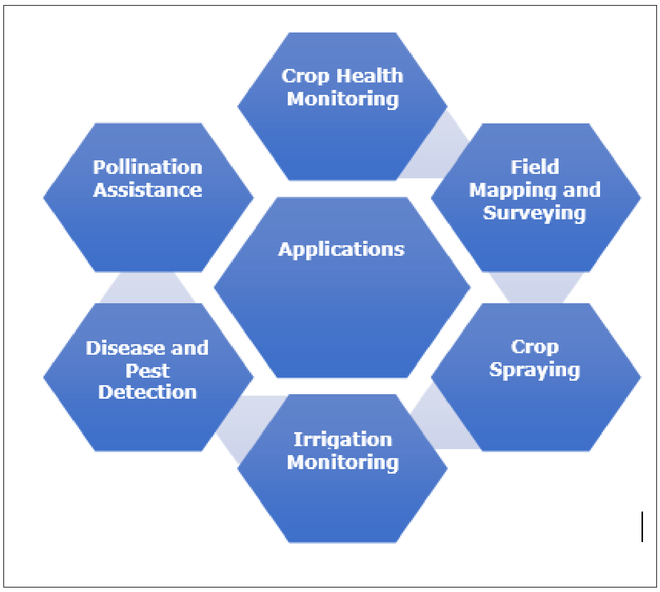

Fig. 4. Drone applications.

using UAVs to detect diseases in crops such as maize, wheat and sugar beet. Multispectral and hyperspectral sensors have been pivotal in identifying disease symptoms, showcasing the potential of UAVs in early disease management(8)

***Pest and disease detection*:** Crop diseases are categorized as bacterial, viral, or fungal and can be destructive. Infrared cameras on drones allow them to view inside plants (33). Image-based tools play a significant role in detecting and identifying plant diseases in cases where human evaluation is unreliable, particularly with the expanded coverage made possible by UAVs (34). While RGB and multispectral images have been the preferred methods for obtaining information about the areas under study, the efficacy of hyperspectral and thermal images has also been examined (35). Using drone-captured footage, a deep learning-based method was suggested to effectively identify plant diseases, exhibiting exceptional competence in crop disease classification and detection (36). Using indices like the Normalized Difference Vegetative Index, a method for gathering and evaluating multispectral images to assess crop health was presented, particularly in vineyards (37).

***Crop scouting*:** The number of plants within a specified area can be quantified by utilizing UAV, thus eliminating the need for manual entry into the paddock (38). Drones equipped with hyperspectral cameras exhibit the capacity to detect variations in the chemical composition of plants, a crucial cue that often signifies a wide range of problems, such as diseases or inadequate water supplies (39). Integrating UAV imagery with satellite data is pivotal for precision agriculture. Implementing photogrammetric techniques to process multispectral data has proven to be a swift, dependable and cost-effective way of evaluating crops (40).

***Agricultural spraying*:** Chemicals, such as insecticides and fertilizers, can be sprayed using drones to assess the fields' and crops' spatial variability. The combination of UAV technology and sprayer systems has the potential to offer a platform for vector control and pest management (1). A created hexacopter-mounted sprayers' droplet density, sizes, spray uniformity, pressure rate of the liquid and field and laboratory evolutions are all examined (41). By including the entire field, UAV assessment of crop nutrient status can significantly improve producer or agronomic consultant advice for application rate. According to research, monitoring may be carried out using specialist camera sensors, including optical and thermal cameras, in conjunction with scientific UAVs (42). Drones have been tested on various crops, including pineapple, papaya and cabbage, showcasing adaptability in different agricultural contexts (9). Research demonstrated that UAVs effectively controlled diseases like leaf spot and rust, with optimal spray volumes identified for best results(10)

***Drone seed applications*:** Drone Seed is an enterprise that has recently conducted trials on implementing spraying drones to sow seeds in the ground. Moreover, this process involves water application to the planted seeds, aiming to diminish the need for human involvement (43). Research shows that Drone Seeds' application of water and seeding via spraying is consistent with the growing trend of drone use for precision agriculture. This strategy can enhance resource efficiency and lessen human intervention requirements (44). Another demonstration provides more evidence, showcasing how well autonomous drones can plant seeds in rice fields (45).

***Field mapping and analysis*:** UAVs integrated with advanced mapping algorithms and Global Positioning System (GPS) technology can generate 3D representations of agricultural fields, thereby assisting farmers in evaluating the contour of the land, drainage systems and soil inconsistencies. This invaluable information facilitates the development of tailored management approaches for specific field areas, guiding the efficient implementation of irrigation and drainage strategies (46). The advancement of processing chains for UAV imagery, incorporating the utilization of novel spectral cameras, has further augmented the potential of these tools in precision agriculture (47). Additionally, the utilization of UAVs to monitor crop fields through the employment of multispectral and thermal imagery has been successfully demonstrated, thereby enabling the mapping of variations in soil moisture, temperature and nutrient composition (48). It is exceedingly valuable in monitoring and evaluating plant stresses, encompassing water levels, diseases, nutritional insufficiencies and pests (49).

***Nutrient management and soil health*:** Using UAVs for real-time monitoring, fertilizer applications may be further optimized and balanced plant nutrition can be promoted (50). Precision agriculture might be revolutionized by UAVs fitted with sophisticated sensors, which can capture high-quality aerial photos in real time for nutrient deficit identification and crop health evaluation (51,52). With this technology, farmers may address nutrient inadequacies in their fields immediately. However, its full potential must be ensured that UAVs are built to allow efficient interaction with their sensors, enabling real-time data processing and analysis (53).

***Pollination assistance*:** Drones have the potential to serve as an effective solution to counteract the decrease in natural pollinators, albeit additional investigation is necessary to comprehend any potential detrimental consequences (54) fully. The Mirco UAV was developed by the National Institute of Advanced Industrial Science and Technology (AIST), Japan. has been designed to assist in artificial pollination through robots. These robots employ a highly innovative approach, utilizing gel-coated animal hair to carry pollen (55). Equipped with cameras, GPS and AI technologies, these UAV robots also harness wind power to facilitate artificial pollination. However, it has been observed that the wind force generated by the UAVs disperses the pollen asymmetrically, posing a challenge and prompting future research endeavours (56,57).

Irrigation monitoring and management: A potential solution to irrigation problems in agriculture involves employing drones fitted with infrared cameras (58). These drones can improve crop management and arrangement by assisting in identifying regions with either too much or too little moisture. Waterlogging and salinity are two issues that have traditionally arisen when irrigation was introduced into desert environments (59). However, using UAVs in accurate farming, encompassing irrigation monitoring can tackle these concerns (60).

Advantages of Drones Over Traditional Methods

Agricultural yield optimization is essential for the farming sector to plan and make decisions effectively. Maximizing crop output entails examining several variables, including market prices, nutrient input levels, soil variability and environmental conditions (61). Agricultural drones, equipped with sensors and cameras, transform the farming industry by delivering up-to-the-minute data to facilitate well-informed decision-making (62). Using advanced methods like multispectral imaging and thermal mapping, UAVs can identify plants' health, gauge water scarcity and analyze soil composition. It empowers farmers to enhance their resource allocation, including irrigation, fertilization and pest management (63). It has been discovered to possess greater cost-effectiveness and efficiency than conventional aircraft or satellite-based platforms in precision agriculture and remote sensing(64). Drone spraying mechanisms in farmers can attain land that may be excessively saturated or otherwise challenging for humans to access.

Another advantage of this utilization is excluding humans from the pesticide spraying process, significantly diminishing the potential for chemical pollution (7) (Table 1). With an emphasis on tracking and increasing production, drones in precision agriculture have recently attracted a lot of attention (65). Multispectral cameras installed on agricultural drones make them an effective tool for maximizing crop productivity. They offer high-resolution photos that are useful for determining problem regions and evaluating the health of crops (25). Farmers may utilize UAVs to obtain an aerial viewpoint to detect differences in crop health, nutrient availability and pests across different regions. This data enables them to generate prescription maps for specific fertilizer applications (32).

Agricultural Drones in Yield Optimization

In contemporary agriculture, UAVs, such as agricultural drones, are utilized more frequently to maximize productivity. By providing accurate indices and high-resolution crop photos, these drones help farmers make well-informed decisions on agricultural management (5). It can improve agricultural production and growth monitoring by utilizing a variety of sensors and Internet of Things (IoT) technologies (66). Increased agricultural yields may be achieved by automating farming tasks like sowing, pesticide spraying and soil sampling using drones and IoT sensors (67).

Many studies have highlighted the potential of remote sensing methodologies in agriculture, particularly those involving drones. The ability of UAV-based remote sensing to identify plant pests and offer diagnostic data on soils and crops (68,69). An actual illustration of how photogrammetric methods and UAV data are used to assess plant vitality for precision farming applications (40). Agriculture might undergo a revolution to combine these technologies, increasing productivity and sustainability (70). These tools enable prompt intervention and maximum crop output by identifying illnesses, nutritional deficiencies and crop stress before they become apparent to the human eye (32). Drones have been instrumental in agriculture in planning crop management activities, monitoring to reduce production losses and problem-scouting (52).

Smart sensors and open-source technologies in contemporary drones have increased their use in agriculture (32). Precision farming has been transformed by drones, which offer high-quality, real-time aerial photography of various environmental parameters, such as soil moisture, humidity and temperature (71). Farmers may maximize crop productivity by using this data to apply pest control techniques more effectively, modify fertilization methods and optimize irrigation schedules. Furthermore, a large portion of farming may be automated with drones, which can automatically plant seeds, fertilize soil and apply pesticides (71). Reducing the need for pesticides in pest control can be achieved by integrating autonomous spraying UAVs with remote weed mapping (72)

Challenges and Limitations of Using Drones in Agriculture

Aerial technology adoption for smallholder farmers: The utilization of unmanned aerial vehicles in the field of agriculture offers a range of prospects as well as obstacles. Although they possess the potential to serve numerous objectives, such as overseeing crops and ensuring the well-being of livestock, their efficiency is constrained by technical limitations like the duration of flight and the maximum weight they can carry (73). The primary focus for small-scale farmers lies in the financial investment needed to obtain and sustain drone technology. Acquiring skills to aid in imagery processing may be necessary for an ordinary farmer, leading to potential expenses. This circumstance can impede the utilization of UAV technologies by individual farmers with limited agricultural acreage (74). Moreover, obtaining proper training to operate drones and analyzing the data they gather can pose a challenge for certain farmers (75).

Technological limitations of agricultural drone: The utilization of supplementary technologies such as big data analytics and cloud computing can further augment the capabilities of drones in the agricultural sector (76). Drones can spray pesticides more precisely and efficiently, while the initial expenses are higher (77). The constraints of the UAV pertain to the size and dimensions of the inexpensive UAVs' sensors. Typically, the smaller or medium-sized amateur models chosen are inherently less stable and lack precision (78). Moreover, low-cost UAVs face limitations in achieving specific altitudes due to their relatively less potent engines. The path-planning systems' lack of a professional pilot, the high-speed, ultra-low scenario,

Table 1. Commonly used agriculture UAV types and specifications (13)

Agriculture UAVs	UAV Type	Potential Application
eBee SQ	Fixed wing	RGB imagery, Spanning vast areas of every flight, Soil Temperature
Sentera PHX	Fixed wing	Weed management, Pest Management, Crop health monitoring
Lancaster 5	Fixed wing	Plants counting and number, plant quality, Creating prescription maps
HoneyComb	Fixed wing	Navigating, Surveillance, Soil H_2O levels, Air pressure
AgEagle RX-60	Fixed wing	Aerial Imaging, Crop health monitoring, Maps prescription
DJI Matrice 600 Pro	Multirotor	Plants counting, Navigating, Aerial photography
Dji matrice 210	Multirotor	Firefighting, Pipeline inspection
Sentera NDVI	Multirotor	Crop health monitoring, Plant counting
AgBot	Multirotor	Plant height, Assessing plant quality

the data downloading function during the real-time application, the size and payload to prevent bottlenecks and the software for its automatic processing are some of the issues that must be taken into account when using UAVs (79).

***Regulatory and operational barriers for agricultural drones*:** Another disadvantage arises from the limitations of UAV technology. Most commercial UAVs have a limited flight time, typically 20 minutes to 1 hour, which restricts the area they can cover in each flight. UAVs with longer flight times tend to be more costly. Furthermore, the successful utilization of UAVs is susceptible to weather conditions. For instance, the flight should be delayed in the case of strong winds or heavy rain (74). The navigation of diverse regulatory frameworks and the resolution of apprehensions regarding privacy. Within the region of Sub-Saharan Africa, the acquisition of a permit for the operation of drones encounters impediments due to regulations that are either excessively limiting or insufficient (80). Drone usage in agriculture has unique benefits but also needs rigorous processing and data quality evaluation. Despite these challenges, the agricultural sector holds immense prospects for drones, as they enhance productivity and alleviate the burden on human resources (81).

***UAVs and job displacement in agriculture*:** The concern regarding UAVs potentially displacing daily wage labourers is multifaceted. While UAVs enhance efficiency in various sectors, their integration may lead to job displacement in specific areas. UAVs are increasingly utilized for tasks traditionally performed by humans, such as building inspections and wildlife monitoring, which may reduce the demand for manual labour in these fields. The shift towards UAV technology necessitates training and skill development, which can lead to new employment avenues for workers willing to adapt (11). While UAVs may replace specific jobs, they also create new opportunities in UAV operation, maintenance and data analysis, potentially offsetting job losses (12). UAVs may threaten specific low-skill jobs but also pave the way for new roles and skill enhancement, suggesting a complex relationship between technology and employment. However, the transition may not be seamless and some workers may face challenges in adapting to these changes.

Future Prospects of Drones in Farming

Drone use in agriculture is proliferating and it has a lot of promise, such as increasing agricultural yield and saving labour costs (81). Advanced drone sensors and imaging capabilities make them helpful in managing fruit crops. They allow precise treatments, early disease and pest identification and increased yield (82). It increases competitiveness in arable crop production by providing options for yield estimation, continuous monitoring and decision assistance (83). It offers a promising solution to feeding a growing population while minimizing environmental impact. They can also be used for biodiversity conservation, crop health monitoring and precision agriculture (3). The widespread adoption of these technologies requires collaboration and support from stakeholders in the agriculture sector. Drones, hyperspectral cameras and machine learning algorithms have all greatly enhanced data gathering and analysis in agriculture. This is especially true when identifying crop stress, disease outbreaks and nutritional deficits (82,84). These developments have enabled farmers to respond to crops promptly, optimizing crop growth and yields (84,85). Significant benefits can be gained in precision agriculture and environmental monitoring with the ongoing advancement of UAV technology, including image processing techniques, cost reduction, longer flying times, better batteries, new camera designs and improved sprayers and nozzles (23).

The potential of UAV-based remote sensing for agricultural applications has already been demonstrated by experimental research and as these technologies advance, the advantages will become even clearer (87). Precision agriculture can benefit from increased efficiency, better crop monitoring, disease diagnosis and control and more accurate pesticide application with UAVs (88). Drone technology in agriculture is set to revolutionize and develop significantly, with enormous potential for sustainable food production. Farmers can make educated decisions about irrigation, fertilization and pest control because of the real-time, high-resolution data collecting that drones provide (90). Drones allow farmers to collect high-resolution data on crop health, soil conditions and environmental variables in real-time. This data allows for precise and focused treatments. This is made possible by developments in sensors, artificial intelligence and data analytics (86). Drone technology combined with robotic platforms and autonomous systems will transform farming operations by cutting expenses associated with human resources, increasing productivity and lessening their adverse environmental effects (91).

Conclusion

Drones are rapidly transforming the agriculture sector by enabling precision farming and data-driven decision-making for farmers. Drones' aerial view and analytical capabilities give farmers unmatched oversight of their lands and crops. They can monitor crop health and map fields, enable targeted application of inputs and provide data-based recommendations to boost productivity. This allows for optimized resource management, risk mitigation, maximized yields and minimized environmental impact. While drones face limitations like battery life, data processing constraints and skill gaps, the technology continuously improves. With sustained progression and greater assimilation of aerial and ground sensor networks, drones are poised to unleash their immense potential. As farmers progressively adopt next-generation agriculture solutions, drones will empower them with the tools and insights to significantly enhance efficiency, yields and incomes. Drones have already elevated global agricultural productivity over the last decade. With food demand increasing, drones will skyrocket as mainstream precision agriculture tools - helping strengthen world food security through sustainable production. The future of agriculture lies in emerging technology and drones are leading the charge by merging data-driven intelligence with farmers' traditional know-how.

Acknowledgements

I am grateful to my family and friends for their continuous support and encouragement towards completing this review article. I am equally indebted to my mentors, whose wise words and profound knowledge have significantly contributed to this study. We also thank the Department of Remote Sensing and Geographic

Information System authorities, Tamil Nadu Agricultural University, Coimbatore, for their support and facilities.

Authors' contributions

NAK (Nithiya Ashok A K) and MD (Muthumanickam D) conceptualized the study. NAK and MD developed the methodology and carried out the formal analysis. NAK and MD conducted the investigation. NAK and MD wrote the original draft. NAK, MD and RKP (Ragunath K P) contributed to writing the review and editing of the manuscript. MD, PP, KR and KP provided supervision. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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