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REVIEW ARTICLE

Application of agricultural drones in vegetable cultivation: A comprehensive review

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Abstract

Drones are unmanned aerial vehicle used for aerial data collection and spraying. The application of Agricultural drones (Spraying drones) in vegetable cultivation had a significant impact on farming practices. Spraying drones equipped with cameras and sensors can capture high-resolution images of crops, allowing farmers to identify potential issues such as pest infestations, disease outbreaks and nutrient deficiencies. Farmer's efficiency is increased in terms of using Agricultural drones. It includes cost-effectiveness, return on investment (ROI), labour savings and improvements in productivity. The use of Agricultural drones, assisting farmers in tackling current challenges and ensuring future food production. Agricultural Drones enable farmers to monitor large areas of vegetable crops fields quickly, saving time and helps the farmers to achieve sustainable and financially sound operations compared to traditional methods. This precision information minimizes resource wastage and ensures optimal conditions for crop growth and yield. It potentially reducing labour costs and increasing the efficiency. It is cost-effective provides timely data leads to improved yields and reduced costs associated with over-fertilization and pesticide use. Research has shown that Agricultural drones can increase productivity up to 30 %. A study conducted in the United States indicated that Agricultural drones save farmers an 15 % in operational costs, primarily through more precise resource allocation. While drones offer a futuristic approach to agriculture, their application in vegetable crop management is fraught with challenges. As the agricultural sector continues to evolve, it will be crucial to weigh these disadvantages against the potential benefits to determine the role of drones in the future of vegetable crop management.

Keywords

effectiveness; efficiency; real-time data; sensors

Introduction

In recent years, the introduction of drone technology has revolutionized various industries, including agriculture, engineering, military and expanding its applications. UAV's have evolved significantly since their inception originally designed for military applications, now widely used in commercial and recreational contexts (1). According to the Federal Aviation Administration (FAA), as of 2023, there are over 1.7 million registered drones in the United States alone, enhances a growing interest and trust in drone technology. Moreover, the global drone market was valued at approximately $22 billion in 2021 and is projected to reach $42 billion by 2026, signifying a compound annual growth rate (CAGR) of about 14.5 %. This growth can be attributed to a variety of factors, including advancements in battery life, the precision of sensors and the development of artificial intelligence capabilities. Drones are being deployed across multiple industries, facilitating processes and increasing efficiency. Some of the most prominent sectors utilizing drone technology include agriculture, construction, logistics and environmental monitoring.

In agriculture, farmers harness drones for precision agriculture. Agricultural drones equipped with multispectral sensors can gather detailed data on crop health, soil conditions and irrigation needs. This data assists farmers in making informed decisions, ultimately increasing yield and reducing waste (2). A study by the National Agricultural Aviation Association indicated that farmers using drone technology increases the crop yield improvements of up to 10 to 15 %. The global agricultural drone market is projected to reach USD 6.4 billion by 2026, growing at a compound annual growth rate (CAGR) of 32.5 % from 2021 (3). The adoption of drone technology in vegetable crops is a significant contributor to this growth, as it offers innovative solutions to several challenges faced by farmers. Recent studies indicate that nearly 25 % of vegetable farmers in developed countries have integrated drone technology into their farming practices. This adoption rate is influenced by factors such as the need for efficient resource management, pest control and crop monitoring. Specifically, drones facilitate aerial imaging, enabling farmers to collect and analyze data related to crop health, soil conditions and irrigation needs (4). By utilizing data collected via drones, farmers can optimize resource allocation, such as water, fertilizers and pesticides. This leads to more sustainable farming practices, as it reduces waste and minimizes environmental impact. Statistics from the Food and Agriculture Organization of the United Nations suggest that precision agriculture can increase crop yields by up to 20 % while conserving resources. Furthermore, drones can assist in crop mapping and yield prediction. They provide detailed aerial imagery that can be used to identify variations in crop health across different fields. This information is crucial for farmers to make informed decisions regarding planting, irrigation and harvest timing. Drones have become indispensable tools for modern cold crop farming operations. In vegetable cultivation, drones offer a range of applications like enhanced efficiency, productivity and sustainability. It helps in monitoring crop health, assessing frost damage, detection and management, precision agriculture, crop mapping and inventory, spraying and irrigation. Due to increase in global population and climate change, modern agriculture must enhance production efficiency (5). Vegetable production is important for human nutrition and has a significant environmental impact. To interpret this challenge, the horticultural sector needs to modernize and utilize advanced technologies such as drones to increase productivity, improve quality and reduce resource consumption. These devices, known as Unmanned Aerial Vehicles (UAV) due to their agility and versatility plays a crucial role in monitoring and spraying operations (6).

The advancement of satellite remote sensing reduces the burden of conventional methods of fertilizer application. In this aspect UAVs is significant due to its high spatial resolution, cost-effectiveness and easy interpretation without ground truth. As a part of the agricultural industry, drones are being employed for various operations like aerial surveillance, mapping, land inspection, monitoring, spraying fertilizers, monitoring pests and diseases (Table 1). The diverse kinds of drones are being tested to determine the most creative space in agriculture, horticulture and farming. Fixed-wing drones suit the purpose of crop fertilization, albeit their large structure requiring a large space for take-off and landing comes in the way (7).

Drones are unmanned aerial vehicle used for aerial data collection and spraying. A quad copter, is unique design of UAVs which has four rotors in their model. The lift of quadcopter is generated by these rotors and in four rotors, the two opposite rotors are turn in clockwise direction and the other two turn in counter clockwise direction (8). The quadcopter movement around the axis includes pitch (backward and forward), roll (left and right) and yaw (clockwise and counter clockwise).

Drones based sensors

Multispectral cameras which capture imagery across multiple wavelengths, can be used for the detection of differences in crop health and stress levels. Thermal imagery can detect temperature variations in crops, which can indicate abiotic and biotic stress (9). LiDAR sensors can create detailed 3D maps of terrain and vegetation, providing valuable information of crop structure and canopy height. GPS and navigation systems provides an essential information for precise positioning and navigation of drones, helps in accurate data collection and mapping**.** Computers or onboard processors are used for real-time data processing and analysis and used for controlling drone flight paths. Before arrangement, farmers or operators plan flight paths and mission parameters using specialized software and this software accounts for factors like crop type, field size and desired data resolution.

Data collected by Agricultural drones can inform precision irrigation strategies, deals with vegetable crops receive the optimal amount of water based on their specific needs (10). Data collected by Agricultural drones can be integrated with farm management software, allowing for better decision making and overall farm planning. It can be arranged regularly throughout the growing season to monitor crop progress, enabling farmers to adapt management practices as needed in real-time. The combination of sensors enables drones to perform a wide range of tasks across industries from recreation, entertainment, scientific research and commercial application (Table 2) (11).

Table 1. Drone application in vegetable crops (7)

S. No.	Vegetable crops
1.	Weed mapping and management
2.	Irrigation management
3.	Crops spraying
4.	Health monitoring of vegetation and detection of diseases
5.	Growth monitoring of vegetation and estimation of yield

Table 2. Drone based sensors used in vegetable crops (9-11)

S. No.	Sensor type	Function	Applications in vegetable cultivation	Benefits
1	**Multispectral Sensor**	Captures images in multiple wavelengths (visible, near-infrared, red-edge, etc)	Crop health monitoring (NDVI, NDRE analysis) Detecting nutrient deficiencies Monitoring plant stress	Early disease/stress detection Precision fertilization Improved yield prediction (9)
2	**Thermal Sensor**	Measures temperature variations in crops	Detecting water stress and optimizing irrigation Identifying diseased plants Greenhouse temperature monitoring	Efficient water uses Early detection of plant diseases Controlled greenhouse environment (9)
3	**RGB Camera (Optical Sensor)**	Captures high-resolution images of crops	Mapping farm fields Detecting pest infestations and disease outbreaks Assessing crop growth stages	Improved visual field monitoring Early pest/disease detection Better decision-making for crop management (9, 10)
4	**LiDAR (Light Detection and Ranging) Sensor**	Uses laser pulses to create 3D maps of fields	Measuring plant height and canopy density Creating topographic maps for precision irrigation Monitoring plant growth patterns	Accurate crop health monitoring Optimized irrigation planning Better land management (10)
5	**Hyperspectral Sensor**	Captures detailed spectral data for advanced crop analysis	Detecting early-stage plant diseases Identifying nutrient deficiencies Monitoring soil health	Higher precision in disease/ nutrient deficiency detection Reduced crop losses Improved soil and plant management (11)
6	**Gas Sensor**	Detect gases like nitrogen, CO_2 and ammonia	Monitoring greenhouse air quality Assessing soil respiration and microbial activity	Optimized greenhouse conditions Enhanced soil health analysis (11)

Crop growth monitoring

A comprehensive list of crop growth monitoring in various vegetable crops (tomatoes, lettuce, cabbage, carrots, onions, Pepper, beans, etc) was shown (Table 3). Crop growth monitoring in vegetable crops is a critical aspect of modern agriculture that involves the continuous observation and assessment of crop development to maximize yields, minimize losses and ensure sustainable farming practices (12). The innovation revolutionized agriculture by providing real-time data on crop health, water stress and nutrient deficiencies, enabling farmers to make informed decisions to optimize yields. The widespread adoption of digital farming tools and software, such as farm management systems and IoT devices, which allow farmers to collect and analyze data on soil conditions, weather patterns and crop performance (13, 14). These tools have enhanced the precision and efficiency of crop monitoring, leading to improved productivity and sustainability in vegetable crop production.

Crop growth monitoring in vegetable crops using spraying drones has revolutionized the agricultural industry in recent years. This technology has the potential to significantly improve crop yields, reduce input costs and minimize environmental impact. Initially, drones were used for aerial imaging and mapping of farmland, but their capabilities have since expanded to include real-time monitoring of crop growth and health (15). The development of low-cost, lightweight drones with advanced sensors has made this technology accessible to a wide range of farmers, including those growing vegetable crops. The impact of using Agricultural drones for crop growth monitoring in vegetable crops has been profound (16). Agricultural drones enable farmers to monitor their crops more frequently and accurately, allowing them to detect issues such as nutrient deficiencies, pest infestations and disease outbreaks early on. This early detection allows farmers to take timely action to mitigate these issues, leading to improved crop health and higher yields (17).

Drones also offer the potential for more sustainable agriculture practices, as they can help optimize irrigation and fertilizer use based on real-time data. However, there are also

Table 3. Crop growth monitoring using drones in vegetable crops (12-24)

S. No.	Vegetable crop	Growth parameter monitored	Drone sensor used	Monitoring method	Key indicators	Actionable insights
1	Tomato	Plant Height, Leaf Area Index (LAI)	LiDAR, Multispectral	3D Canopy Mapping, NDVI	Canopy coverage, Leaf expansion	Adjust fertilizer & irrigation (12)
2	Chilli	Fruit Development	RGB, Hyperspectral	Image Analysis, Color Segmentation	Fruit size, Color changes	Harvest timing optimization (12, 13)
3	Beetroot	Biomass Accumulation	Multispectral	NDVI, NDRE, LAI Analysis	Leaf area growth	Adjust fertilization & irrigation (14, 15)
4	Lettuce	Uniformity of Growth	RGB, Multispectral	Canopy Density Mapping	Uneven growth patches	Precision nutrient application (16)
5	Pepper	Canopy Development	RGB, Multispectral	Vegetation Indices (NDVI, GNDVI)	Canopy density, Color changes	Optimize spacing & nutrients (17)
6	Bhendi	Flowering & Fruit Set	RGB, Hyperspectral	Flower & Fruit Detection	Number of flowers/ fruits	Predict yield & manage pollination (18)
7	Beans	Root Development Estimation	Multispectral	Spectral Reflection Analysis	Leaf Vigor, Growth rate	Optimize irrigation & nutrients (19)
8	Carrot	Foliage Density	RGB, LiDAR	Canopy Volume Estimation	Leaf cover, Growth uniformity	Adjust spacing & inputs (20)
9	Cabbage	Head Formation	RGB, Multispectral	Canopy Size & Texture Analysis	Head size, Leaf curling	Adjust water & nutrients (21)
10	Soyabean	Pest & Disease Monitoring	Multispectral, Thermal	Vegetation Stress Indices	Discoloration, Hotspots	Early intervention with treatments (22, 23)
11	Onion	Leaf Length & Density	Multispectral, RGB	NDVI, Plant Height Estimation	Leaf number, Color intensity	Adjust nitrogen application (24)

challenges associated with the use of drones, including the high initial cost of the technology, regulatory hurdles and data management issues (18). The integration of drones with other precision agriculture technologies, such as satellite imaging and IoT devices, will enable more comprehensive monitoring and management of vegetable crops (19). This technology has the potential to revolutionize farming practices, leading to higher yields, reduced input costs and more sustainable agriculture.

The use of drones in agriculture has become increasingly popular due to their ability to capture accurate and timely data on crop conditions. Agricultural drones equipped with multispectral cameras can capture imagery in different wavelengths of light, allowing farmers to assess crop health based on factors such as chlorophyll levels, nitrogen content and water stress. This technology has proven to be particularly useful in monitoring vegetable crops, which are often susceptible to environmental stressors and pest attacks (20). For example drones can identify areas of low moisture content in a field, allowing farmers to adjust irrigation schedules to prevent water stress in their crops. Similarly, drones can detect signs of pest infestations, such as discoloration or defoliation, enabling farmers to target pesticide applications more effectively. Drones can provide farmers with detailed insights into crop growth patterns and variability within their fields. By conducting regular drone flights over their fields, farmers can create high-resolution maps of crop health, allowing them to identify areas of poor performance and implement targeted interventions (21). This level of precision agriculture can lead to significant improvements in yield, quality and profitability for vegetable farmers (22). In recent years, several influential individuals have contributed to the development and adoption of drone technology in agriculture. Crop growth monitoring in vegetable crops using drones has the potential to transform the way farmers manage their crops and make decisions about production. By providing real-time data on crop health, growth patterns and pest infestations, drones can help farmers improve their yields, reduce input costs and minimize environmental impact (23, 24).

Nutrient and water stress detection using drones

Nutrient and water stress detection in vegetable crops (tomatoes, chilli, brinjal, pepper, onion, etc) using drones (Table 4) has become an increasingly important topic in the field of agriculture (25). With the ever-growing global population, there is a heightened need for efficient ways to monitor and manage crop health to ensure food security (26). Drones, also known as unmanned aerial vehicles (UAVs), have emerged as a valuable tool in agriculture due to their ability to provide real-time data on crop conditions (27). The impact of nutrient and water stress detection in vegetable crops using drones with farmers experiencing significant improvements in crop health and yields. By utilizing drones to monitor nutrient levels and water availability in their fields, farmers can identify problem areas early on and take corrective actions to prevent crop losses (28). This proactive approach has led to a more sustainable and environmentally friendly agricultural practices, reducing the use of chemical fertilizers and water resources. The use of drones has enabled farmers to optimize their inputs, leading to higher yields and increased profitability (29). The use of drones for nutrient and water stress detection in vegetable crops offers numerous benefits, including improved crop health, higher yields and reduced production costs. Farmers can make informed decisions based on real-time data collected by drones, leading to more efficient resource management and sustainable farming practices (30). The growing interest in nutrient and water stress detection in vegetable crops using drones reflects the increasing demand for sustainable and efficient farming practices (31). Drones offer a cost-effective and timely solution for monitoring crop health and detecting stress factors, allowing farmers to make informed decisions

Table 4. Nutrient and water stress detection using drones in vegetable crops (25-39)

S. No.	Vegetable crops	Type of stress	Drone sensor used	Detection method	Indicators	Corrective action
1	Tomato	Nutrient Deficiency (N, P, K)	Multispectral, Hyperspectral	Spectral Vegetation Indices (NDVI, PRI)	Yellowing leaves (N), Purple tint (P), Scorched edges (K)	Fertilizer application (25)
2	Chilli	Water Stress	Thermal, Multispectral	Canopy Temperature, NDWI	High canopy temp, wilted leaves	Adjust irrigation schedule (26)
3	Beetroot	Nutrient Deficiency (N, Mg, Ca)	Hyperspectral	Chlorophyll Content Analysis	Pale leaves, tip burn	Balanced nutrient solution (27)
4	Lettuce	Water Stress	Thermal, RGB	Leaf Reflectance, Wilting Detection	Wilted, dry edges	Optimize irrigation (28, 29)
5	Pepper	Nutrient Deficiency (N, Zn, K)	Multispectral	Leaf Reflectance, NDVI	Stunted growth, leaf curling	Foliar spray or soil amendment (30, 31)
6	Turnip	Water Stress	Thermal	Canopy Temp Analysis	High leaf temp, curling leaves	Irrigation adjustment (32, 33)
7	Carrot	Nutrient Deficiency (Boron, P)	Hyperspectral	Spectral Index Analysis	Cracked roots, purple foliage	Boron or phosphorus supplements (34, 35)
8	Beans	Water Stress	Multispectral, RGB	Wilting Index	Wilting, poor root development	Increase soil moisture (36)
9	Cabbage	Nutrient Deficiency (N, Ca)	Multispectral	Vegetation Index, Chlorophyll	Yellowing, tip burn	Apply appropriate nutrients (37)
10	Soyabean	Water Stress	Thermal, Multispectral	NDWI, Canopy Temp	Leaf wilting, poor head formation	Optimize irrigation (37, 38)
11	Onion	Nutrient Deficiency (P, K, S)	Hyperspectral	Reflectance Spectroscopy	Yellowing, delayed bulb formation	Soil fertilization (38, 39)
12	Radish	Water Stress	Thermal	Soil Moisture Estimation	Dry leaf tips, slow growth	Adjust irrigation (39)

and optimize their yields. There are still barriers to widespread adoption, such as limited access to technology, lack of technical expertise and regulatory constraints (32). The future of nutrient and water stress detection in vegetable crops using drones for enhancing agricultural productivity and sustainability. Advances in drone technology, such as the development of hyperspectral imaging sensors and AI-driven analytics, will enable more accurate and detailed monitoring of crop health (33).

Nutrient and water stress detection in vegetable crops using drones is a cutting-edge technology that has revolutionized the agricultural industry (34). The use of drones for detecting nutrient and water stress in vegetable crops has gained significant traction in recent years. Drones equipped with advanced sensors can capture detailed images of crops, allowing farmers to analyse the health and vitality of their plants (35). By detecting nutrient deficiencies and water stress early on, farmers can take proactive measures to ensure optimal crop growth and yield. The impact of using drones for nutrient and water stress detection in vegetable crops is profound. This technology has enabled farmers to make data-driven decisions and optimize their farming practices for increased efficiency and productivity (25, 36). By accurately identifying areas of nutrient deficiencies or water stress, farmers can apply targeted treatments and irrigation practices, leading to healthier crops and higher yields (37). By providing farmers with valuable insights into the health of their plants, drones can help reduce waste, increase efficiency and improve overall crop quality. The initial cost of purchasing drones and the required technology can be prohibitive for small-scale farmers. Additionally, there are concerns about data privacy and security, as drones capture sensitive information about crop health and farming practices (38, 39).

Pest and disease monitoring

Pest and disease monitoring plays a vital role in crop production. Pest and disease monitoring in vegetable crops (tomatoes, chilli, brinjal, bell pepper, onion, etc) using drones (Table 5). The monitoring of pests and diseases in vegetable crops has been a longstanding practice in agriculture (40). Farmers have traditionally relied on visual inspections and scouting techniques to identify and manage pest and disease outbreaks. Technological advancements have revolutionized the way pests and diseases are monitored in vegetable crops (37, 41). Drones, are unmanned aerial vehicles (UAVs), have become increasingly popular for agricultural applications due to their ability to capture high-resolution imagery and collect data in real-time (42). By utilizing drones, farmers can quickly and accurately identify areas of infestation or disease, allowing for targeted treatment and prevention measures. The use of drones for pest and disease monitoring in vegetable crops has had a significant impact on the efficiency and effectiveness of agricultural practices (43). Drones enable farmers to cover large areas of crops in a minimal time of period allowing for more frequent monitoring and earlier detection of pests and diseases (44).

Drones equipped with advanced imaging technology, such as multispectral cameras and infrared sensors, can provide valuable insights into plant health and stress levels. This information can be used to optimize irrigation schedules, detect nutrient deficiencies and improve overall crop management practices (45). By integrating drone technology into pest and disease monitoring efforts, farmers can make more informed decisions and improve the sustainability of their farming operations (46). Drones can cover large areas of farmland quickly and provide high-resolution images that enable farmers to make data-driven decisions and take timely action (47, 48).

Table 5. Pest and disease monitoring using drones in vegetable crops (40-48)

S. No.	Vegetable crop	Pest/Disease	Drone sensor used	Detection method	Key indicators	Actionable insights
1	Tomato	Early Blight, Late Blight	Multispectral, Thermal	NDVI, Disease Stress Mapping	Yellow/brown spots, Wilting	Apply fungicides, remove infected plants (40, 41)
2	Chilli	Whiteflies, Aphids	RGB, Hyperspectral	Insect Detection via Image Analysis	Leaf curling, Honeydew residue	Introduce bio controls, insecticides (42)
3	Lettuce	Downy Mildew	Multispectral, Hyperspectral	Spectral Analysis, NDVI	Yellow patches, Leaf deformation	Improve air circulation, apply fungicides (42)
4	Bhendi	Thrips	RGB, Thermal	Leaf Texture Analysis	Leaf bronzing, Stunted growth	Use sticky traps, biopesticides (43)
5	Pepper	Powdery Mildew	Multispectral, RGB	Reflectance & Canopy Analysis	White powdery spots	Apply sulfur-based fungicides (43)
6	Soyabean	Spider Mites	Thermal, Multispectral	Heat Signature & Canopy Stress Detection	Wilting, Stippling on leaves	Increase humidity, introduce predatory mites (40, 44)
7	Beans	Alternaria Leaf Blight	Hyperspectral, RGB	Leaf Spotting & Stress Mapping	Brown leaf spots, Wilting	Apply fungicides, remove infected leaves (45)
8	Carrot	Carrot Rust Fly	Multispectral	Canopy Health & Color Change	Wilted foliage, Stunted roots	Use row covers, crop rotation (45)
9	Cauliflower	Black Rot	Hyperspectral, Thermal	Chlorophyll Breakdown Analysis	V-shaped yellow lesions	Avoid overhead irrigation, apply bactericides (43)
10	Cabbage	Cabbage Worms	RGB, Multispectral	Pest Movement Detection	Chewed leaves, Presence of larvae	Introduce natural predators, spray Bt (46)
11	Onion	Onion Thrips	Multispectral, RGB	Leaf Texture & Stress Analysis	Silvery streaks, Curling leaves	Use neem oil, insecticide (47)
12	Garlic	Fusarium Basal Rot	Thermal, Hyperspectral	Soil Moisture & Stress Mapping	Yellowing leaves, Root decay	Improve drainage, apply fungicides (48)

Spraying various inputs in vegetable crops

Spraying various inputs in vegetable crops (tomatoes, chilli, bhendi, bell pepper, onion, etc) using drones has revolutionized the agricultural industry by providing a more efficient and effective method of applying fertilizers, pesticides and herbicides (49). Drones, also known as unmanned aerial vehicles (UAVs), have become increasingly popular in recent years due to their ability to cover large areas in a short amount of time, reduce labour costs and minimize environmental impact. The impact of using drones for spraying various inputs in vegetable crops has been far-reaching. Farmers are now able to apply fertilizers, pesticides and herbicides more efficiently, leading to higher crop yields and reduced environmental contamination (50). The use of Agricultural drones has helped to reduce labour costs and improve overall farm productivity. Drones can cover large areas quickly and accurately, reducing the time and labour required for traditional spraying methods (51). One of the main concerns is the potential for pesticide drift, which can occur when chemicals are not applied properly or under unfavourable weather conditions (52). There are concerns about the cost of investing in drone technology and the lack of regulations governing their use in agriculture.

Embracing drone technology can yield numerous benefits for farmers. First, Agricultural drones significantly enhance efficiency in data collection and monitoring. Traditional methods of crop inspection often involve labor-intensive processes, consuming substantial time and resources. Agricultural drones can cover large areas in a fraction of the time, allowing farmers to conduct regular assessments without major disruptions to their schedules. Moreover, drone technology aids in optimizing resource use, thereby potentially lowering cultivation costs (53). For example, Agricultural drones can help precisely determine where fertilizers or pesticides are needed most, reducing overall chemical usage. By applying these inputs only where necessary, farmers can cut costs while mitigating the environmental impact of excess chemical application.

Additionally, Agricultural drones facilitate better decision-making through the provision of real-time data. Farmers can make informed choices based on accurate assessments, leading to improved crop management. For instance, by understanding variations in soil health and moisture levels, farmers can apply water and fertilizers more efficiently (54). This targeted approach fosters healthier crops and maximizes yield potential, ultimately contributing to greater profitability.

Despite the potential advantages, the initial investment in Agricultural drone technology can be significant, posing a financial burden for many farmers. The cost of purchasing drones, coupled with the necessary software and training to operate them, can be prohibitive, particularly for small-scale farmers. According to recent studies, the total cost of entry, including drones, cameras and subscriptions to data services, can range from several thousand to tens of thousands of dollars. Furthermore, while drones can enhance efficiency, their use may also incur additional operational costs. Farmers must consider expenses related to maintenance, repairs and possible regulatory fees associated with drone operation (55). Additionally, training staff to effectively utilize drone technology can add to labor costs, thereby increasing the overall cost of cultivation. In many regions, government regulations require drone operators to obtain licenses, adhere to specific flight paths and comply with safety standards. Navigating these regulatory requirements can present another layer of expense and complexity (56).

In light of these challenges, the decision to adopt drones in farming requires careful consideration. Farmers must weigh the initial costs against the potential benefits realized from improved operational efficiency and increased yields. Many experts suggest that over time, as drone technology becomes more widespread and competitive, prices will decrease, making it more accessible for a broader range of farmers. Moreover, it is essential to recognize that the successful integration of drone technology necessitates a shift in mindset. Farmers must be willing to embrace change and invest in their education regarding the use of technology. Collaborative efforts between agricultural tech companies, government agencies and educational institutions can provide valuable support in training farmers and demonstrating the advantages of drone technology. Several research studies shows that farmer’s efficiency is increased using agricultural drone technology. It also suggests that the both positive (increased) and negative (decreased) aspects of cost of cultivation and it is more efficient to farmers now-a-days to increase the yield and productivity (57).

Spraying various inputs in vegetable crops (tomatoes, chilli, bhendi, pepper, onion, etc) using drones has revolutionized the way agriculture is conducted. This advanced technology combines the precision of drones with the efficiency of spraying chemicals or fertilizers on vegetable crops. Drones offer a sustainable solution by allowing targeted spraying of inputs, thereby reducing the overall environmental impact of crop production. The high cost of drone technology and the need for specialized training for operators can be a barrier to adoption for small-scale farmers. Spraying various inputs in vegetable crops using drones is a transformative technology that has the potential to revolutionize agriculture. As drones become more integrated into farming practices, it is essential to consider both the positive and negative aspects of this technology to ensure sustainable and responsible use in the agricultural sector (58).

Application of drones in cole crops

Drones can be useful in managing cole crops like lettuce, spinach, cabbage, etc. It helps in monitoring crop health, apply fertilizers or pesticides precisely and helps in assisting planting seeds or seedlings in large fields. Their aerial view provides valuable data for optimizing irrigation and detecting early signs of diseases or nutrient deficiencies. Drones equipped with multispectral or thermal cameras can capture high-resolution images of cold crops. These images can be processed to identify areas of stress, disease, or nutrient deficiencies. Early detection helps the farmers to take corrective action immediately and minimizing crop loss (59). Agricultural drones enable precise application of fertilizers, herbicides and pesticides shown in Fig. 1 and 2. They can be programmed to spray only specific areas, reducing chemical usage and minimizing environmental impact. This precision also helps in preventing damage to the crops themselves.

Fig. 1. Agricultural drone spraying in vegetable crops (cauliflower).

Fig. 2. Agricultural drone spraying in vegetable crops (cabbage).

Drones use cameras to collect image data and sensors to gather information and timely decision-making on large farms. This data has a high spatial resolution in centimetres, providing direct visual views around large areas of crops. Drones are small devices, electronically controlled by remote control and have also been developed to be controlled using Android and Apple iOS systems. These aircraft provide us with two-dimensional images which can be processed and linked to GPS and thermal images can be obtained. Some drones are capable of autonomously planting seeds or seedlings (60). It can be useful in large fields of cold crops. Manual labour for planting can be time-consuming and labour-intensive. Drones can cover large areas quickly and accurately, ensuring optimal spacing and planting depth. Aerial imagery captured by drones can provide valuable information into soil moisture levels and crop water stress. Farmers can use this data to optimize irrigation schedules, ensuring that cold crops receive the right amount of water at the right time. This not only maximizes yield but also conserves water resources. Drones equipped with advanced imaging technologies can help estimate crop yields by analysing plant density, size and health. It aids in better crop management decisions, including harvesting schedules and resource allocation. Drones can create detailed 3D maps of cold crop fields, providing farmers with valuable information about field topography and soil variability. This data can optimize planting patterns, drainage systems and field management strategies. Drones equipped with thermal cameras can detect temperature variations in cold crop fields, helping farmers identify areas with poor drainage, water stress, or diseases like powdery mildew. This information used for targeted interventions to improve crop health and yield. Drones collect the data using aerial imaging, multispectral sensors and other technologies. It can be analysed through advanced algorithms and machine learning technologies. Using drone imagery analysis farmers can detect cold crop field that requires attention, areas with nutrient deficiencies or signs of pest infestation (61). Drone can be monitored by remote sensing technologies. Using these technologies farmers can quickly identify the issues and timely remediations can be taken. Drones equipped with environmental sensors to monitor the environmental factors such as soil moisture, temperature and humidity in cold crops. It deals with how the environmental factors impact the crop growth and yield. Drones can capture the aerial imagery that documents the condition of cold crop fields throughout the growing season. It provides a record of compliance with environmental regulations and farm management practices. Drones offer a wide range of applications in cold crop farming, enabling farmers to improve crop management, increase efficiency and enhance sustainability (62).

Pest and disease monitoring

Cole crops, which include broccoli, cabbage, cauliflower and kale, are vital components of global agriculture. They are rich in nutrients and are critical for food security. However, these crops are susceptible to a range of pests and diseases that can severely affect yield and quality. Traditional methods of pest and disease monitoring often rely on manual inspections, which can be labour-intensive and inconsistent. With advancements in technology, particularly Unmanned Aerial Vehicles (UAVs) or drones, farmers are now able to enhance their monitoring capabilities.

One of the primary advantages of using Agricultural drones for pest and disease monitoring is their efficiency. Traditional monitoring methods often require extensive walking through fields, which can be time-consuming and might not provide a comprehensive overview of the crop health. Agricultural drones can cover several acres in a fraction of the time (63). For example, Agricultural drone equipped with multispectral cameras can capture images that reveal the health status of crops at various wavelengths. This technology allows for detecting stress conditions in plants, which may indicate pest damage or disease, even before symptoms become visible to the naked eye.

Farmers can receive immediate feedback on the conditions of their fields, allowing for rapid decision-making. For instance, if a drone identifies signs of aphid infestation or fungal infections, farmers can quickly apply the necessary treatments to mitigate damage. Real-time data can also track the effectiveness of applied treatments, enabling farmers to adjust their pest management practices accordingly.

Several case studies highlight the successful integration of Agricultural drone technology in monitoring cole crops. In the United States, a study conducted in California demonstrated that drones could effectively identify disease in broccoli plants. Researchers used Agricultural drones equipped with multispectral sensors that detected variations in plant chlorophyll levels, indicating distress due to disease. This timely identification enabled farmers to apply targeted treatments and ultimately reduced crop loss (64).

Similarly, farmers in the Netherlands have successfully utilized Agricultural drone technology for monitoring cabbage crops. By analysing drone imagery, they were able to detect infestations of cabbage root fly early in their lifecycle. This early detection allowed for timely intervention, significantly improving yields and reducing pest control costs.

Drones have several impacts on cole crops. It includes monitoring, crop health, growth and moisture levels and provides valuable information for farmers to optimize the irrigation and fertilization in cole crops. It deals with pest infestations in cold crops early and allows targeted pesticide application and minimize the crop damage. For mapping, it can create detailed 3D maps of cold crop fields. For harvesting, it is still in development, drone technology deals with automating the harvesting process in cole crops, potentially reducing labour costs and increasing the efficiency (65).

Cole crops (cucumber, cabbage, lettuce, spinach) yield can be enhanced using drone technology. These crops were severely affected by pest infestation, diseases, frost damage, climatic factors, etc. Drone Technology implemented in this crop reduce the infestation and damages. These crops leaves were so small, so the drone spraying effectiveness is crucial. Drone spraying in cole crops is still in progress. In future, it can be effective for reducing the pest infestation and can get better yield (66).

Challenges of drone spraying in vegetable crops

* Drones can apply pesticides, fertilizers, herbicides, to specific areas of vegetable crops. It reduces the waste and minimize the impact. Cole crops are sometimes difficult to access terrain due to uneven terrain or wet conditions. It is very difficult to spraying in a challenging environment. Drones can navigate these areas easily.
* Drones being an airborne, it can overcome the problem very easily. Using drone technology, time and labour efficiency can be reduced and yield can be increased. Drones spraying reduce the risk of exposure to harmful chemicals for farm workers. It promotes the safer working conditions in cold crop farming (67).
* Drones have limited battery life, which are exacerbated in cold weather conditions. It leads to shortening of flight time and limiting the area covered during each operation. Usage of drones are highly restricted in cole crops area due to climatic factors. It limits the drone utility. It is costly and expensive. Operating a drone requires a skill and training experts.
* In cole crops the climatic condition is worse, so it requires an additional layer of complexity and potential cost. Drones equipped with cameras have privacy concerns. In cole crops, it leads to consequences and legal challenges, deviating from the primary focus of crop management. Drones are affected by adverse weather conditions. It leads to malfunctioning of the system. Limited payload capacity is more pronounced in cole crops (68).
* Cold temperature reduces the battery life, leads to shorter flight plans. Lithium polymer batteries, used in drones are highly affected by cold weather. The RPM of drone motors drop in cold weather, it reduces the lift and manoeuvrability. It leads to uncontrolled landing or crash. Barometric pressure is higher in cold weather, it affects the drone's altitude readings and stability.
* Cold weather has strong winds, it affects the drone's stability and cause accident. The air gets denser due to decrease in temperature. It affects the drone's ability to generate lift, requires more power to maintain altitude.
* The materials used in the drone's construction contract in cold weather, affects the drone's structural integrity and flight dynamics. Sensors and electronic components are affected by cold weather leads to inaccurate readings or malfunctions (69).
* Drones are used for covering large areas and not a complete replacement of human power. Drones are used for Precision agriculture and deployed in Pesticides for dispersing and reduced human intervention in Agriculture works instead man-made spray techniques in cereals and pulse crops. According to the temperature and crops height it will differs a lot (70).
* Increasing the altitude the dispersion of pesticides and the liquid we are using it will spread in large area will make an drift and possible chance of dispersion of liquid in buffer areas and outside the fields and will not disperse up to the ground when it comes to crops like tomato, brinjal, etc. The drone will not able to cover up to the last leaf or the fruits in the crops while increasing the altitudes increasing in payload and increasing the dispersing liquids or pesticides will be the solution for the complete disease (71, 72).
* When it comes to crops like cabbage, carrot, cauliflower, cabbage, radish, beetroot, etc are growing high altitude requires a nominal or minimum temperature because the due drops on the crops or in the leaves in the vegetables are the smaller bad conditions for drone (73, 74).
* The amount of dispersing liquid will vary from the man-made spraying and drone. The maximum SOP was restricted for all crops in the agriculture sector up to 20 litres per hectare the amount of discharge will not give a major impact in diseased crops (75).

The adoption of drone technology in vegetable crop production has brought a range of positive impacts to the farming industry (76). Drones enable farmers to gather real-time data on crop conditions, allowing them to make informed decisions about irrigation, fertilization and pest control. This leads to more efficient use of resources, increased crop quality and higher yields. Drones also provide farmers with a new tool for precision agriculture, allowing them to create detailed maps of their fields and target specific areas for intervention. Additionally, drones can be equipped with sensors and cameras that can detect early signs of disease or nutrient deficiencies, enabling farmers to address problems before they escalate (77).

Despite the numerous benefits of using drones in vegetable crop production, there are also some negative aspects to consider. One of the main concerns is the cost of acquiring and operating drone technology, which can be prohibitive for small-scale farmers (78). Additionally, there are regulatory challenges related to drone use, such as restrictions on flying near airports or populated areas (78). Privacy issues also arise from the use of drones for surveillance, as farmers must navigate concerns about capturing images of neighbouring properties or infringing on individuals' rights (79). Data security is another potential risk associated with drone technology, as the information collected by drones could be vulnerable to hacking or unauthorized access (80). The impact of pie charts involved in drone applications for vegetable crops is significant. By using pie charts to visualize data collected by drones, farmers can easily identify patterns, trends and potential issues in their crops (81, 82). This allows them to make informed decisions about crop monitoring, drone spraying, pest, infestation, weed detection, ultimately leading to higher yields and improved crop quality (Fig. 3) (83).

Future Aspects

* There are various perspectives on the use of drones in vegetable crop production, with some stakeholders embracing the technology for its potential to enhance farming practices and others expressing concerns about its implications for privacy and data security.
* Proponents of drone technology argue that it offers a cost-effective and efficient way to monitor crops, optimize inputs and increase yields. They also highlight the environmental benefits of using drones, such as reducing pesticide use and minimizing water consumption.
* The future of drone application in vegetable crops holds great promise for further innovation and advancement. As drone technology continues to evolve, there is an improvement in drone capabilities, such as longer flight times, higher payload capacities and enhanced sensors. There will also be opportunities for greater integration of drones with other technologies, such as automated irrigation systems and robotic harvesters.
* While drones offer a futuristic approach to agriculture, their application in cole crop management is fraught with challenges. From the shortened flight times due to cold-affected batteries to the heightened sensitivity to weather conditions, drones face an uphill battle in the cold. As the agricultural sector continues to evolve, it will be crucial to weigh these disadvantages against the potential benefits to determine the role of Agricultural drones in the future of cole crop farming.

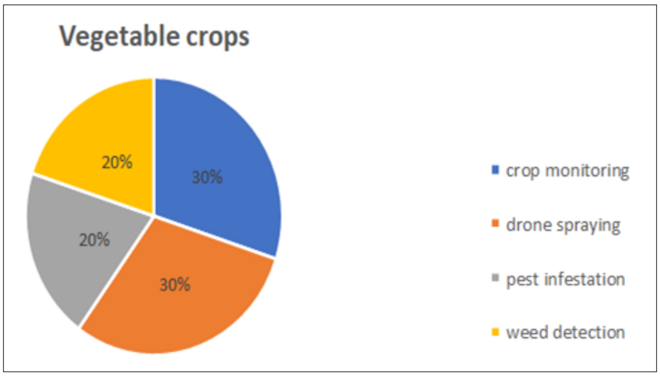

Fig. 3. Percentage of drone applications in vegetable crops (8).

* The use of artificial intelligence and machine learning algorithms will enable drones to analyse data more efficiently and provide farmers with actionable insights in real-time. Overall, the future of drone application in vegetable crops highly beneficial, with the potential to transform farming practice in horticulture.
* Despite the advantages, the integration of Agricultural drone technology in agriculture is not without its challenges. One of the primary drawbacks is the high initial investment required to acquire and maintain drone systems. Farmers, particularly smallholders, may find it challenging to allocate sufficient funds for such advanced technology. Furthermore, the ongoing costs associated with software updates, maintenance and training personnel can add to this financial burden. Another significant concern is the regulatory environment. In many regions, drone usage is subject to strict regulations that can hinder their widespread adoption. Issues related to airspace restrictions, privacy concerns and liability laws may create barriers for farmers wishing to utilize drones.
* One promising avenue for mitigating these drawbacks is through cooperative models. By forming cooperatives, farmers can pool their resources to share the costs associated with purchasing drones and obtaining necessary training. Such collaboration not only reduces individual financial burdens but also fosters knowledge sharing and collective problem-solving. For example, a group of vegetable farmers could jointly invest in a drone system, allowing them to access cutting-edge technology that they might not afford individually. This approach is already being tested in various regions, demonstrating its potential to enhance productivity and sustainability.
* Another strategy to address the financial concerns related to Agricultural drone technology is the development of affordable, user-friendly drone solutions. As advancements in technology continue, manufacturers are exploring options to produce low-cost drones designed specifically for smallholder farmers. These drones would feature simplified controls, making them accessible to individuals with limited technical expertise. Additionally, providing solution packages that include drones, training and ongoing support can incentivize farmers to adopt this technology. Initiatives by organizations such as the Food and Agricultural Organization (FAO) and private sector companies to develop affordable drone solutions could significantly impact the agricultural landscape.
* Regulatory challenges must also be tackled to facilitate Agricultural drone adoption in vegetable crops. Industry stakeholders can collaborate with governments to develop clearer regulations and guidelines for drone usage in agriculture. Engaging in discussions about the safe integration of drones into national airspace systems and addressing privacy concerns can pave the way for smoother operations. Furthermore, establishing pilot programs that demonstrate the benefits of drone technology can provide valuable insights and inform regulatory frameworks. Countries like the United States have initiated such programs, allowing agricultural

stakeholders to demonstrate the effectiveness of drones in enhancing crop management.

* Training and education represent another crucial element in mitigating the drawbacks of drone technology. As agricultural practices evolve, farmers must be equipped with the necessary skills to utilize drones effectively. Agricultural extension services can play a pivotal role in providing education and training on drone operation, data interpretation and best practices. This can help build a skilled workforce capable of maximizing the potential of drone technology in vegetable crops. Additionally, incorporating drone technology and its applications into agricultural curricula at universities and colleges can prepare the next generation of farmers to navigate this technological landscape.
* Moreover, improving data management and integration can enhance the benefits of drone technology in agriculture. Drones generate vast amounts of data and efficient systems for data analysis and integration are essential to derive meaningful insights. Developing platforms that consolidate data from drones with other sources, such as satellite imagery and weather data, can provide comprehensive decision-making tools for farmers. Precision agriculture platforms that integrate various data streams enable more informed choices regarding planting schedules, irrigation and pest management. This holistic approach can significantly mitigate risks associated with crop management while optimizing resource utilization.

Conclusion

In conclusion, the application of Agricultural drones in vegetable crops (tomato, chilli, bhendi, onion, carrot, lettuce, etc) represents a significant shift in agricultural practices, with the potential to revolutionize the way farmers monitor and manage their crops. While there are challenges and considerations to address, the benefits of using Agricultural drones in agriculture far outweigh the drawbacks. One of the primary uses of Agricultural drones in vegetable crop management is crop monitoring. Agricultural drones equipped with multispectral and thermal cameras can capture high-resolution images that reveal critical information about plant health. For instance, these cameras can detect variations in plant temperature and chlorophyll content, which may indicate water stress, nutrient deficiencies, or pest infestations. By identifying these issues early, farmers can take timely action to mitigate potential losses. This proactive approach leads to healthier crops and consequently, higher yields.

A study conducted in Spain highlighted those farmers using Agricultural drones for irrigation management achieved up to a 30 % reduction in water usage while maintaining crop productivity. As drone technology offers several advantages, the spraying operation of cole crops is still in testing progress due to climatic and environmental factors. Even though it has several problems, it provides efficient and precise application of pesticides, fertilizers and other agrochemicals. It can navigate terrain and inaccessible areas and make it as a valuable tool for farmers. It enhances crop health and yields, minimizing the environmental impact and reduce the labour costs.

By embracing this drone technology and leveraging its capabilities, farmers can improve their efficiency, productivity and sustainability. As the field of Agricultural drone application in vegetable crops continues to evolve, it is essential for stakeholders to collaborate, share knowledge and address any concerns to ensure that this technology is used responsibly and ethically. By harnessing the power of drones, farmers can pave the way for a more innovative in vegetable crops and resilient agricultural industry.

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Authors' contributions

YV contributed in conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing - original draft. RJ contributed in conceptualization, data curation, formal analysis, software, supervision, visualization, writing - review & editing, writing - original draft. DM contributed in data curation, formal analysis, investigation, methodology, project administration, resources, writing - review and editing. KT contributed in conceptualization, data curation, Formal analysis, methodology, Writing -original draft. MK contributed in resources, software, supervision, validation, visualization, writing - original draft.

Compliance with ethical standards

Conflict of interest: The authors declare that the research was conducted without any commercial or financial relationship that could be constructed as a potential conflict of interest.

Ethical issues: None

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