PLANT SCIENCE TODAY
Vol 12(sp3): 01–09
https://doi.org/10.14719/pst.9391

eISSN 2348-1900

REVIEW ARTICLE

Economic and environmental impact of drone technology in Indian agriculture: An overview

Rahul Disaniya[1], Varadha Raj S[2*], Prahadeeswaran M[1], Ragunath Kaliaperumal[4], Shanmugam Pagalahalli Sankaran[4], Pangayar Selvi R[5], Rajkumar R[1] & Sarita Jat[6]

[1]Department of Agricultural Economics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Basic and Social Science, Forest College and Research Institute, Tamil Nadu Agricultural University, Mettupalayam 610 301, Tamil Nadu, India

[3]Centre for Water and Geospatial Studies, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[4]Department of Agricultural Entomology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[5]Department of Physical Sciences & IT, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[6]Department of Agronomy, Sri Karan Narendra Agriculture University, Jobner, Jaipur 303 329, Rajasthan, India

*Correspondence email - varadharajstnauecon@gmail.com

Received: 08 May 2025; Accepted: 09 July 2025; Available online: Version 1.0: 26 September 2025

Cite this article: Rahul D, Varadha RS, Prahadeeswaran M, Ragunath K, Shanmugam PS, Pangayar SR, Rajkumar R, Sarita J. Economic and environmental impact of drone technology in Indian agriculture: an overview. Plant Science Today. 2025;12(sp3):01–09. https:/doi.org/10.14719/pst.9391

Abstract

Drones or small unmanned aerial vehicles, present a variety of opportunities for the agricultural industry. Drones are widely utilized for real-time airborne photography, sensor data collecting, pesticide spraying, soil analysis and fertilisation and animal monitoring in agriculture. Drones for agricultural spraying are being actively promoted by the Indian federal government. The main goals of these "Kisan drones" are to reduce spraying times, improve the effectiveness and efficiency of using resources for agricultural applications (pesticides, etc.) and lessen the negative health impacts of manually applying pesticides. Drones are anticipated to have a future role in aerial imaging, surveying and transportation in farming. This study shows that the state is actively promoting a more liberalized drone-friendly policy and offering large financial incentives to businesses, groups and specific farmers to buy, use or manufacture drones as needed. In addition to saving time, drones are said to use resources efficiently, saving a significant amount of water. The cost-per-acre unit economics of drone spraying is beginning to catch up with that of manual labour and it reduces input costs by 18 %-20 % and increases crop yields by 30 %-100 % through precision farming. Drones also cut labour and operational costs while enabling efficient coverage of large areas quickly. Environmentally, they lower chemical usage by up to 50 %, conserve water by up to 90 % and reduce the carbon footprint by 25 %. Additionally, drones help reduce post-harvest losses by 50 % and support job creation, making them a key tool for sustainable and productive farming in India.

Keywords: crop health monitoring; kisan drone; precision farming; spraying; UAVs

Introduction

Drone technology integration in agriculture has altered traditional farming methods worldwide in recent years. Drones, also known as unmanned aerial vehicles (UAVs), have a variety of uses, from precision farming and crop monitoring to yield optimization and pest control (1). Beyond their technological appeal, it's critical to comprehend the financial effects of drone use in agriculture. In the modern agricultural landscape, drones have taken flight, promising a greener, more efficient future. These unmanned marvels are not only revolutionizing farming but also reshaping the environmental footprints (2). This paper explores the ecological impact of agricultural drones on minimizing input use and waste and achieving sustainable development in agriculture. Drones are widely used for sowing, fertilizer and plant protection chemicals spraying and irrigation. It saves input, time and human health.

Drones can be used to spray pesticides more effectively than labour-intensive, dangerous conventional methods, especially in challenging terrain like hills (3). To gain an understanding of soil conditions, plant health and crop yield prediction, artificial intelligence and machine learning can be combined with high-resolution images taken by drones using NDVI (normalized difference vegetation index) imaging technology (4, 5). If a plant appears stressed, each one can be found independently and examined using image processing methods. With this information, growers may stop illnesses from spreading to other crops by taking preventative measures. Using analyzed insights from data collected by drones and satellite-based remote sensing, timely actions can be taken to reduce the impact of climate change and unpredictable weather, optimize fertilization, rationalize irrigation and prevent losses from biotic stresses such as insect pests and diseases (6).

Drone use in agriculture has various potential uses due to the unprecedented COVID-19 pandemic-related labour shortage that has made physical separation measures necessary. This paper examines the adoption, application and impact of drones to provide valuable insights for crafting policies and sustainably integrating technology. The Indian government has recently issued multiple statements highlighting its commitment to promoting drone technology within the agricultural sector. The government of India is eager to utilize drones known as Kisan, which translates to farmers in Hindi, to enhance the agricultural sector as outlined in the federal budget for 2022–2023. The adoption of Kisan Drones for activities such as nutrient and pesticide spraying, digitizing land records and assessing crops will be promoted. The use of high-capacity drones to deliver fruits, vegetables and fish directly from farms to markets has the potential to initiate a transformative change (2). These products will be delivered straight to the marketplace with little harm, requiring less time and leading to increased earnings for farmers and fishermen. The opportunities that drones offer to the agricultural sector are continually expanding.

Drones are frequently utilized for various functions, including applying pesticides, managing land, gathering real-time imagery and sensor data, conducting soil sampling and fertilization, as well as monitoring animal populations (3). Furthermore, market analysts forecast that within five years, spanning from 2021 to 2026, the drone services market will expand approximately threefold, increasing from USD 5.48 billion to USD 15. This study provides new insights into future agricultural operations by showcasing how drone technology can shift farming from traditional, labour-intensive methods to data-driven, precision-based practices. It highlights drones' ability to optimize resource use, reduce environmental impact and enhance productivity at scale. The objective of this research is to investigate and evaluate the economic effects of drone technology in agriculture, clarifying how it might improve sustainability, lower costs, boost production and promote efficiency in farming operations. This review aims to offer important insights into the economic processes influencing the development of agricultural drone technology by integrating the body of existing literature and empirical data.

Agriculture Drone Market

The worldwide market for agricultural drones was valued at approximately USD 1.7 billion in 2022 and is projected to grow at a compound annual growth rate (CAGR) of 21.2 %, reaching USD 7.9 billion by 2030 (Fig. 1). In agriculture, drones can assist in enhancing crop production, monitoring crops and improving various agricultural processes. Precision agriculture employs drones for multiple tasks, including the application of pesticides, planting and inspecting soil and crop fields.

Adoption of Agricultural Technology

The digital transformation of the agricultural sector is essential for addressing the various challenges that farmers encounter due to fluctuations in resource availability, market demands and environmental conditions. Employing the latest technologies in agriculture can offer numerous benefits, such as reduced costs and enhanced yields. Drones are among the IT-driven smart tools that can replace traditional land survey methods for more efficient farming. Some benefits of using drone technology in agriculture include precise agricultural assessments, financial and time savings, improved yields and effective crop-spraying techniques (4). A recent study projected that by 2025, the global drone market for agriculture would reach $5.7 billion, expanding at a rate of 35.9 %. However, farmers must also navigate several limitations when utilizing drones for crop monitoring. The major problems are non-connectivity and sensitivity to weather, which require special training and experience.

Drones for precision agriculture

In various sectors, drones have been utilized for remote monitoring. The adoption of drones in agricultural crop surveillance has significantly increased over the past few decades. It is anticipated that the drone market within the agricultural field will grow by 80 %-90 % was reported in the earlier studies (10). Compared to satellite imagery, which can be affected by clouds and other environmental factors, drones can

Fig. 1. Global market size of drones Source: Grand View Research, Inc., 2024 (Agriculture Drones Market Size, Share & Growth Report 2024-

provide much clearer results. Furthermore, maintaining drones is easy and cost-effective due to the straightforward process of replacing damaged components after accidents (5).

Agricultural drones can be operated either manually or by setting predetermined flight routes via GPS. The programmed flight of the drone is designed to self-stabilize in stronger winds to capture clearer images. Drones come equipped with a range of features to meet farmers' needs, from basic digital cameras to advanced photography techniques. Because healthy plants reflect infrared light, near-infrared imaging technology is utilized to enhance the quality of images captured by drone cameras (6). The complete field perspective provides more efficient ways to identify specific areas for precision agriculture (PA). Drones have significant potential to improve sustainable farming practices.

The agricultural drone industry is projected to hit $32.4 billion, suggesting that farmers will increasingly recognize the numerous benefits that drones offer compared to conventional methods such as ground surveying (7). The advancements in drone technology have enhanced their ability to operate in complex agricultural landscapes. With the use of spectral imaging and advanced remote sensing, drones have become integral to precision farming (8). Since the 1950s, satellite technology has been utilized for remote sensing to analyze crops and identify temperature and spectral reflectance characteristics that are crucial for agricultural output.

The condition of the crops can be determined by monitoring temperature through RS methods. Drones are capable of delivering high-quality images for low-altitude field spraying and crop assessment (7). Agricultural drones are equipped with advanced cameras capable of capturing high-resolution RGB images across vast areas (9). Software can analyze the drone images and provide insights regarding crop health and productivity. The ability to map field variability and regularly collect data enables more consistent precision agriculture practices and improved decision-making. Drones find applications in various areas, such as precise 3D mapping in farming and preliminary soil investigations. The benefits of drones for farming are discussed in Table 1.

Methodology

The research performed an extensive review of scholarly articles across platforms such as Google Scholar, ResearchGate, Scopus, Science Direct, EMBASE and PubMed, utilizing terms like drone technology and its applications in different sectors. To guarantee that the most recent research was included, the analysis of the data was conducted using publication years ranging up to 2024, ensuring the study reflects the latest technological advancements, policy initiatives and field-level implementations of drone technology in Indian agriculture. This up-to-date analysis offers clearer insights into how drones are currently transforming farm operations and sets a more accurate foundation for predicting their future role in enhancing agricultural efficiency, sustainability and profitability. To enhance the credibility and reliability of the findings, this systematic review exclusively featured peer-reviewed articles.

Data collection process and screening

The findings of the study were centred around drone technology and its applications in various sectors. Specifically, the gathered data encompassed the potential uses, limitations, capabilities and impacts of the technology across different industries. The articles underwent a careful analysis to identify the keywords that appeared in their abstracts and titles, allowing for the categorization of narratives based on the extent of focus on drone technology. The selected articles were then meticulously evaluated to determine their relevance and applicability for the overview. A thorough examination of the titles, abstracts, conclusions and findings was conducted during the selection process to ascertain whether the papers specifically addressed import-export volumes, revenue impacts and types of drone technology use. Only those

Table 1. Principal advantages of drones for farming

Benefit	Technology Used	Applicable Crops	Regions	Economic Benefits	References
Improve the geographical and temporal resolution of sensing.	Remote sensing, UAVs, satellite imagery	Wheat, rice, maize	Global, especially India, the USA and China	Reduces data collection costs and increases decision accuracy	(10-12)
Encourage accurate farming	GPS-guided equipment, sensors	All major crops	USA, Europe, Australia and India	10-30 % reduction in input costs; 15-25 % yield improvement	(13, 14)
Classification and scouting of crops	Satellite imagery (Sentinel, Landsat), drones	Soybean, wheat, corn	North America, Brazil and India	Early problem detection saves up to 20 % of potential losses	(15, 16)
Applying nutrients	Variable rate technology (VRT), soil sensors	Rice, wheat, maize	South Asia, Sub-Saharan Africa and USA	Up to 40 % reduction in fertilizer use	(17-19)
Tracking the dry spell	Remote sensing, soil moisture sensors	Cotton, pulses, wheat	India, Africa and Australia	Reduces irrigation costs and prevents yield loss	(20, 21)
Estimating fossil fuel use	IoT, fuel tracking systems	All mechanized crop systems	USA, EU, mechanized Indian farms	10-15 % energy savings, cost reduction	(22)
Estimating returns	Crop modelling software, AI/ML tools	Cereals, oilseeds, horticultural crops	Global	Helps in crop insurance, market planning and investment	(23, 24)
Preservation of forests and wildlife	GIS, remote sensing, conservation mapping tools	Not crop-specific	Amazon Basin, Central Africa and Northeast India	Supports eco-tourism, forest-based incomes and avoids legal penalties	(25, 26)
Evaluation of water pressure	Pressure sensors, smart irrigation systems	Sugarcane, paddy, maize	Punjab (India), California (USA) and Egypt	Increases water use efficiency up to 30 %, lowers energy use	(27, 28)
Identification of weeds, pests and illnesses	Drones, image recognition and AI-based apps	Wheat, tomato, cotton	India, Brazil and Sub-Saharan Africa	Saves 15-40 % crop loss and reduces pesticide costs	(23, 24, 29)

articles that met the established criteria were chosen for further analysis to provide a comprehensive understanding of the current state of drone technology in various industries.

The filtering process generated a total of 1347 items from the Scopus database and 1210 from Science Direct, without removing any duplicate articles. In the next phase, articles and research papers unrelated to the application of drones in agriculture were excluded. Following that, only case studies demonstrating the aspects and impacts of drone technology in agricultural settings were included. Consequently, 1078 articles were discarded from both the Science Direct and Scopus databases. Duplicate articles were subsequently removed by hand. This led to the selection of 72 articles for further analysis.

Methods

The processes involved in this drone technology research included gathering, cataloguing and organizing; as well as analysis and synthesis. The literature was sourced from online databases, search engines and various technological resources to obtain published papers, reports and studies as primary references. To gain a comprehensive understanding of the topic, we also collected data from white papers and publications within the industry. Fig. 2 presents the process flow of the study.

Impact of drone technology on agriculture

The application of drones in farming provides a modern technological upgrade due to their ability to plan in real time and strategize for both growth and data collection. The drone industry is projected to achieve a value of $200 billion by 2023. Drones can be beneficial for numerous tasks throughout the crop cycle, including:

Examining the soil and pasture

Farmers have found that using drone technology to survey their fields at the beginning of each planting season is a highly effective method. They can take advantage of the 3-D mapping images generated by drones for analyzing soil conditions during seed plugging (30). The valuable information gathered from drone investigations of the soil and pastures can enhance nitrogen management in fields and aid in irrigation planning (31).

Planting

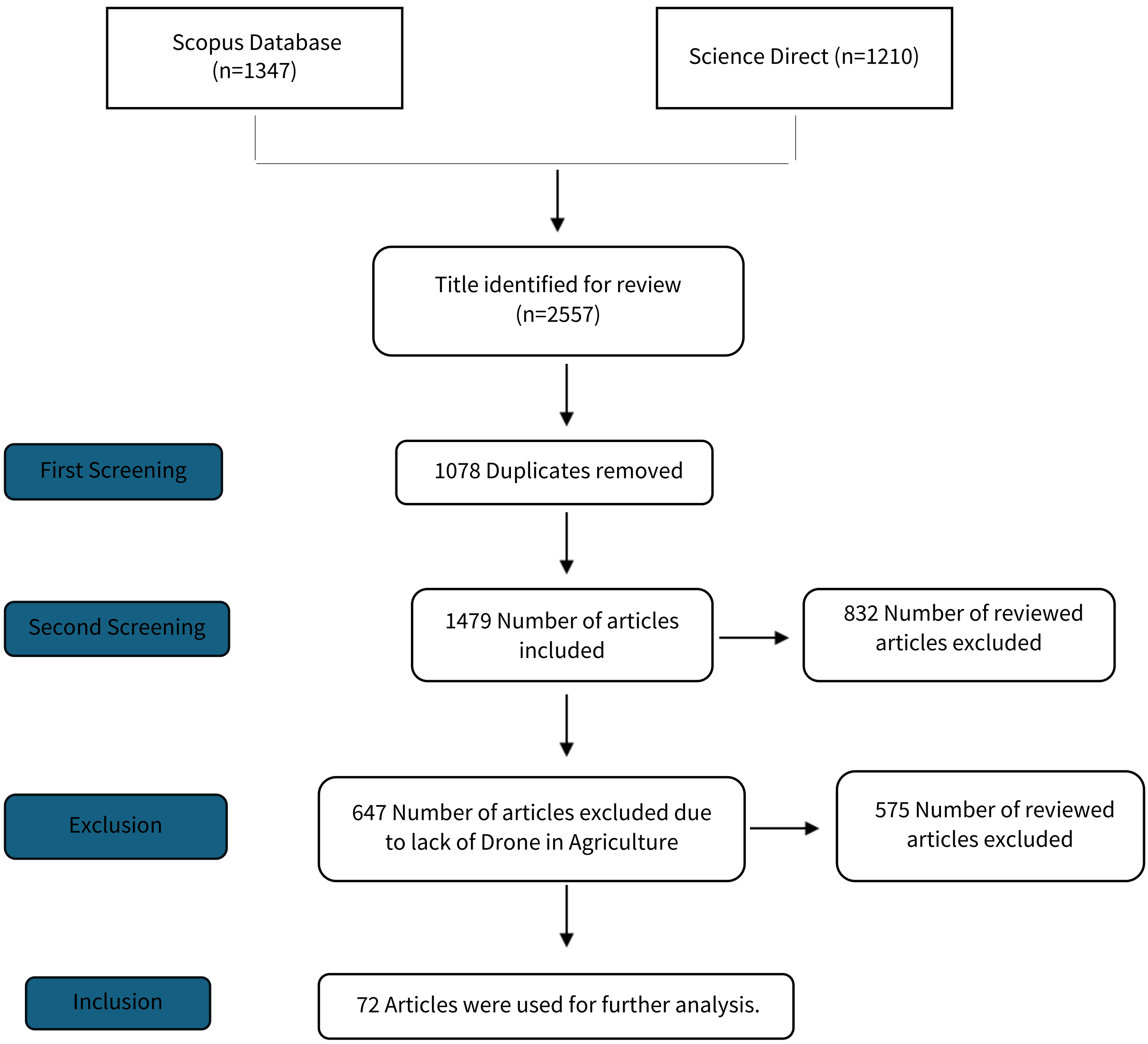

Fig. 2. Flowchart of search, selection and screening of articles

A recent study suggests that drones can be utilized for large-scale tree planting projects. To gather information regarding soil conditions and identify optimal planting locations, the drone surveys a specific region. With five drones and two operators, it is possible to plant 200000 plants within a single day (32). According to the World Economic Forum (WEF), approximately 16 billion trees are cut down globally every year, whereas only 10 billion are replanted, as replanting involves significant planning and financial resources (33). Drone technology can facilitate tree planting in inaccessible areas up to ten times quicker than human workers, with an 8 % reduction in costs. It delivers seed-filled nutrient pods precisely at the correct depth into the soil. Preliminary findings suggest that planting expenses could be decreased by as much as 85 %. Drones are employed to distribute seed pods and fertilizers into the ground, ensuring each plant receives the essential nutrients for healthy growth (34).

Crop monitoring

Crop monitoring is performed using drone technology to pinpoint areas lacking sufficient irrigation or fertilizer, evaluate crop development and detect plant damage caused by storms. Farmers can assess crop yields, thickness and growth using its 2D and 3D images. By analyzing these 2D and 3D visuals, one can uncover inefficiencies in the manufacturing process and gain valuable insights into crop growth. The drone employs sensors to track and identify reflected near-infrared (NIR) light (35). The NIR light spectrum is significant because healthy plants reflect a greater amount of NIR while absorbing more visible light, whereas weaker plants display the contrary behaviour. NIR analysis specifically manages solutions and provides farmers with detailed maps depicting plant health data (6). The use of drones for crop monitoring enables real-time observation of the vegetation index across various regions and crops by spectrally analyzing high-resolution satellite images (36). This insight enables the study of crop development dynamics that are both optimistic and pessimistic.

Plant health assessment

The health of plants can be adversely affected by syndromes even prior to the appearance of clear symptoms such as changes in leaf colour. Although these characteristics may not be visible to the naked eye, they can be detected through cameras and specific filters. Drone technology enables the swift identification of agricultural irregularities and assessment of plant health. Methods like drone mapping and plant health algorithms, such as NDVI, can highlight anomalies and aid in detecting crop stress; however, there are certain issues associated with NDVI (37). Assessing crop health and identifying fungal or bacterial infections in plants are essential. By utilizing both visible and near-infrared light to evaluate crops, a drone-based system can detect plants that reflect varying levels of green and NIR light. This data is used to generate multispectral images that illustrate the health of the plants and capture any changes in their condition.

Disease monitoring

Drone technology has emerged as a powerful tool for detecting plant diseases in Indian agriculture, enabling early diagnosis of issues like yellow rust in wheat, powdery mildew, citrus greening and downy mildew in grapes. Using multispectral and thermal imaging, drones identify disease stress before visible symptoms appear, allowing timely and targeted interventions (38). When an infection is detected at an early stage, a farmer has the opportunity to prevent it from spreading to adjacent plants, for instance, by removing the infected one. Therefore, in situations where human evaluation is unsuitable, erroneous, or not possible, image-based techniques can play an essential role in recognizing and diagnosing plant diseases, especially considering the greater reach provided by unmanned aerial vehicles (UAVs) (39). Although hyperspectral and thermal imagery have been studied, RGB and multispectral images have been chosen as the methods for gathering data about the areas being investigated (40, 41). The latter is mostly utilized to identify indicators of water stress that may be brought on by the specific illness. This leads to economic benefits such as a 20 %-30 % increase in crop yield, up to 52 % reduction in pesticide usage and significant savings in labour and input costs. Environmentally, it reduces chemical runoff, conserves water by up to 90 % and lowers carbon emissions, promoting sustainable and efficient farming practices.

Spraying

To achieve high productivity levels in Indian agriculture, there is a need for production and protective materials. Fertilizers and agricultural chemicals are often essential for eliminating pests and enhancing crop growth. Based on the spatial arrangement of crops and fields, drones can be utilized to apply fertilizers and insecticides. The quantity of pesticides to be applied can differ based on the conditions of the crops or the intensity of the pest infestation (42). The integration of UAVs with sprayer systems presents an opportunity for effective vector control and pest management. This application is specifically designed for large agricultural areas. To conduct extensive spraying operations, larger UAVs with significant lifting capacity are essential (43). The affordable and lightweight Quadcopter (QC) system, often known as an unmanned aerial vehicle (UAV), was suggested by researchers (44). Because of its compact design, this quadcopter system is ideal for both indoor and outdoor agricultural applications. Using an Android device, the quadcopter serves as an autonomous flying tool for distributing fertilizers and pesticides. Real-time Bluetooth connectivity enables the operation of the quadcopter through an Android device. This technology aims to enhance agricultural productivity while reducing common problems faced in the farming sector. The PWM controller on the UAV's spraying system enhances efficiency when pesticides are being applied (45).

An aerial automated pesticide sprayer (AAPS) was created to apply pesticides in low-altitude settings utilizing GPS coordinates, featuring a hybrid design of a blimp and a quadcopter (46). To address this issue, Freyr, a user-friendly, low-cost pesticide-spraying drone with Android app control, was created (47). In both lab and field evolutions, the droplet density, sizes, spray uniformity, pressure rate and liquid discharge of a hexacopter-mounted sprayer are analyzed (48). An electrostatic sprayer with a hexa-rotor UAV was introduced and meant to reduce the amount of insecticide wasted (49). As per estimates from the World Health Organization, there are more than a million instances of pesticide exposure each year. In underdeveloped countries, the use of human-applied pesticides leads to over a hundred thousand fatalities annually. The herbicide disrupts the human nervous system, resulting in various health issues. To safeguard individuals from pesticide poisoning, fertilizers and insecticides are applied using a remotely operated drone (50).

In crop dusting, drones outperform tractors, as they are equipped with tanks that hold insecticides and fertilizers for spraying crops. This method not only reduces costs but also minimizes the risk of worker exposure to pesticides that would typically occur during manual spraying. Drones are particularly useful for applying pesticides in environments where labour is limited. By spraying from lower altitudes, they can lessen environmental pollution and this technology can significantly enhance pest management in both small and large agricultural fields through highly accurate, site-specific applications (51). Researchers from Asia investigated how varying heights of operation and concentrations of pesticides impacted the wheat canopy and controlled powdery mildew utilizing UAV (UAV N-3) spraying parameters (52). Ultimately, this enhances the efficacy of the chemicals applied, thereby reducing their negative impact on the environment by decreasing pollution in both soil and water. This could potentially lead to more sustainable agricultural practices. Drones can spray chemicals more efficiently than traditional methods. Furthermore, it might result in a decreased volume of chemicals utilized, which could help lower input expenses.

The use of micronutrients (including sulphur, magnesium and zinc) along with fertilizers (such as nitrogen, phosphate and potash) represents a crucial economic investment for any agricultural season. Fertilizers are distributed using piloted aircraft or ground-based machinery like tractor-mounted sprayers or pressurized irrigation systems (53). Producers with multiple large land parcels typically prefer the latter method. Due to the height of the aircraft and the variable wind conditions during fertilizer application, they often apply uniform rates across all sprayed fields. Ground equipment is also utilized during the irrigation season to ensure a consistent level of crop nutrition. Utilizing UAV evaluations of crop nutrient status, which assess the whole field, can significantly improve the recommended application rates suggested by producers or agronomic consultants. Research indicates that surveillance can be conducted utilizing scientific unmanned aerial vehicles (UAVs), particularly camera sensors such as thermal and optical cameras and specialized optical filters like Red Edge or hyperspectral cameras (10). Fertilizers and pesticides were applied with the help of accelerometer and gyroscope sensors, allowing for time and labor savings.

Precision farming

Recent studies show that precision agriculture leverages artificial intelligence to create exact, advanced methods that enhance the current knowledge of ideal planting and harvesting techniques, in addition to managing water and fertilizers. Drones equipped with advanced sensors are widely used in precision agriculture for various applications. Water stress in crops is monitored using RGB, multispectral, hyperspectral, or thermal infrared sensors, helping optimize irrigation. Nutrient disorders are detected through RGB, multispectral and hyperspectral sensors, allowing targeted fertilization. Disease monitoring relies on a combination of RGB, multispectral, hyperspectral and thermal sensors to identify infections early. For weeding, hyperspectral and RGB sensors help distinguish weeds from crops for precise removal. Evapotranspiration rates, crucial for water management, are assessed using multispectral and thermal sensors. Additionally, GPS, accelerometers and gyroscope sensors enhance drone navigation and stability during field operations. These methods boost agricultural efficiency and assist in predicting returns on investment for specific crops based on their market segment and pricing (Table 2). Ultimately, the conclusions of the review highlighted the adaptability of agricultural UAVs within the agricultural sector. Nevertheless, numerous challenges and obstacles remain in the initial phases of research and development in the field of artificial intelligence. In this work, we detailed the infrastructure, control and applications of agricultural UAVs that have been further explored or developed. To aid in guiding the future direction of AI research, we present various issues, viable theories and the latest findings in agricultural UAV research.

Results and Discussion

A total of 72 research articles were assessed for the ongoing study on drone technology. The literature search, conducted using various databases and search engines, yielded over a thousand results. However, even though some records contained the phrase "drone technology" in their titles, abstracts or keywords, they were excluded due to their irrelevance to the review topic. Many more papers were disregarded after a thorough examination of the remaining publications due to non-fulfilment of the eligibility criteria. Ultimately, only a limited number of documents were deemed suitable for review. Google Scholar was the primary search engine used for the literature search, although Scopus, EMBASE and PubMed were also utilized. The findings illustrate the progression of drone technology and its impact across various industries. The aim of the present study was to explore the environmental and economic impacts of drone technology. To assess the application of drones in different sectors and their

Table 2. Drone application in a variety of scenarios

Applications	Sensors used	Indicate	References
Water stress observation	RGB, multispectral, hyperspectral or thermal infrared sensors	Indicates moisture stress, helping in timely irrigation to prevent yield loss	(12, 27, 54, 55)
Nutrient disorders	RGB, multispectral and hyperspectral sensors	Indicates yellowing, poor growth, or chlorosis, allowing targeted fertilizer application	(56, 57)
Diseases monitoring	RGB sensor, multispectral images sensor, hyperspectral and thermal sensor	Indicates abnormal leaf colour, wilting and temperature variations signalling early-stage infections	(25, 58, 59)
Weeding	Hyperspectral sensor rgb sensors	Indicates weed locations, enabling precision herbicide spraying or mechanical removal	(24, 60–62)
Evapotranspiration spraying	Multispectral and thermal sensor	Indicates crop water demand, optimizing irrigation scheduling	(6, 27)
GPS sensor	Accelerometer and gyroscope sensors	Indicates the exact location, direction and stability of equipment or UAVs for accurate operations	(41, 61)

economic advantages, a comprehensive review of relevant literature was conducted. The analysis focused on the financial benefits of drone technology, its regional relevance and historical trends. The data indicate that there has been a significant increase in research publications concerning drone technology, with some articles published between 2016 and 2024.

The findings and discussions presented in the review article highlight the substantial disruption that drone technology has introduced to both the environment and economy in Indian agriculture. Drones have certainly initiated a transformative shift by enhancing efficiency in ways that were previously unimaginable and improving ecological resilience. This groundbreaking technology has transformed the agricultural production landscape, overturning traditional farming practices. The use of drones has yielded numerous benefits, including improved yield, precision in agricultural monitoring and a decrease in environmental harm.

Potential issues with drone technology and future directions

It is widely acknowledged that an individual can spray approximately two acres in a day and the labour cost for manual spraying per acre ranges between ₹350 and ₹400. The expenses associated with renting drones for spraying are currently on the higher end, with the average fee for drone spraying being around ₹700 per acre. However, using drones for spraying significantly saves time. The convenience of drones may positively influence crop selection and intensity, among various potential benefits. Consequently, if the price of drone spraying were to decrease somewhat, farmers could consider paying for drone rentals as needed, possibly dominating the spraying market. Furthermore, there are concerns that the lower volume of spray used by drones-requiring less water than traditional spraying-might increase the concentration of chemicals used. In addition to the financial advantages of drone spraying, this aspect must be taken into account, given that food production prioritizes safety, as the use of highly concentrated chemicals raises safety issues.

Drones represent a fairly new technology in Indian agriculture; therefore, when they are adopted, it is crucial to maintain thorough documentation to pinpoint what factors promote or hinder adoption. Farmers cultivating on challenging terrain or growing difficult-to-spray crops may become enthusiastic users of drones. For example, younger farmers might be more open to the idea of drone spraying. To evaluate the effectiveness and cost -efficiency of using drones, farmers might want to experiment with them in specific areas of their fields. This documentation and related research efforts would also contribute to developing a crop-specific drone spraying guide to help farmers make informed decisions. The operation, upkeep and servicing of drones require skilled labour, posing both a challenge and an opportunity. The challenge is to cultivate a workforce of trained individuals in rural areas near farms who can operate drones and deliver services to farmers at an affordable price. Conversely, with over 145 million farms in India, this also opens up job prospects for ambitious young individuals. In the future, if Indian farmers recognize the potential advantages of using drones for agricultural spraying, they may be applied for more advanced purposes. This could lead to enhancements in health and economic conditions for Indian farmers, as well as a more efficient use of agricultural resources.

Conclusion and a way forward

To meet the requirements of a growing population, support farmers' well-being and tackle national and global uncertainties such as the COVID-19 pandemic, the agricultural sector needs to undergo significant transformations. Drone technology, which is rapidly evolving due to its various applications, plays a key role in this change. Drones not only enhance overall agricultural productivity but also promote precision farming practices, offering a pathway for the shift from labour-intensive to technology-driven farming. By providing accurate and reliable information about the condition of agricultural fields, they help decrease human error and the inefficiencies associated with traditional farming methods. Acting as "an eye in the sky," drones are initiating a new era in agriculture. Combining software, sensors, cameras and different analytical tools, drones automatically gather and process data and images into insights and actionable information, significantly minimizing human error. The advantages of drone technology for farmers are twofold: it aids in decision-making and can take over certain tasks in the field faster and with greater accuracy than human labour. However, several barriers hinder the adoption of drone technology in agriculture. It is essential to overcome these challenges to effectively implement drone technology and harness its potential to transform the agricultural sector and improve the lives of millions of farmers in India. The findings of this research will inform policy recommendations aimed at maximizing the advantages of drone technology for both the environment and the economy. These recommendations will encompass the creation of policies and regulations that promote the responsible and sustainable use of drone technology, striking a balance between economic benefits and environmental conservation, while also addressing regulatory structures, technological progress and training programs to ensure responsible and sustainable drone operations.

Acknowledgements

The authors express gratitude to the Department of Agricultural Economics, Department of Basic and Social Science, Centre for Water and Geospatial Studies, Department of Agricultural Entomology, Department of Physical Sciences and IT, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India for providing the required facilities and support throughout the research period.

Authors' contributions

RD participated in the research activities, establishment, statistical data analysis and the writing of the research article. VRS edited and reviewed the research article. Every author reviewed and endorsed the final manuscript. PM worked in methodology and review part. RK involved in conceptualization and administration, SPS worked in review process and editing. PSR involved in software analysis and reviewing. RR participated review and editing and SJ involved writing, review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to disclose.

Ethical issues: None

References

1. Kendall H, Clark B, Li W, Jin S, Jones GD, Chen J, et al. Precision agriculture technology adoption: a qualitative study of small-scale commercial "family farms" located in the North China Plain. Precis Agric. 2022;1–33. https://doi.org/10.1007/s11119-021-09839-2
2. Singh P. Drones in Indian agriculture: trends, challenges and policy implications. 2023. https://www.researchgate.net/publication/375085397
3. Zhao J. Drone technology for precision agriculture: advancements and optimization strategies. Highlights Sci Eng Technol. 2024;111:185–91. https://doi.org/10.54097/h70j2c34.
4. CIMMYT Economics Program. The adoption of agricultural technology: a guide for survey design. Mexico: CIMMYT. 1993. https://repository.cimmyt.org/server/api/core/bitstreams/ea28bad2-2522-4119-9499-6104d53e6afa/content.
5. Kalaiselvi P, Chaurasia J, Krishnaveni A, Krishnamoorthi A, Singh A, Kumar V, et al. Harvesting efficiency: the rise of drone technology in modern agriculture. J Sci Res Rep. 2024;30(6):191–207. https://doi.org/10.9734/jsrr/2024/v30i62033
6. Xia T, Kustas WP, Anderson MC, Alfieri JG, Gao F, McKee L, et al. Mapping evapotranspiration with high-resolution aircraft imagery over vineyards using one-and two-source modeling schemes. Hydrol Earth Syst Sci. 2016;20(4):1523–38. https://doi.org/10.5194/hess-20-1523-2016
7. Singh N, Gupta D, Joshi M, Yadav K, Nayak S, Kumar M, et al. Application of drones technology in agriculture: a modern approach. J Sci Res Rep. 2024;30(7):142–52. https://doi.org/10.9734/jsrr/2024/v30i72131
8. Khanal S, Kushal KC, Fulton JP, Shearer S, Ozkan E. Remote sensing in agriculture-accomplishments, limitations and opportunities. Remote Sens. 2020;12(22):3783. https://doi.org/10.3390/rs12223783
9. Zhao J. Drone technology for precision agriculture: advancements and optimization strategies. Highlights Sci Eng Technol. 2024;111:185–91. https://doi.org/10.54097/h70j2c34
10. Al-Arab M, Torres-Rua A, Ticlavilca A, Jensen A, McKee M. Use of high-resolution multispectral imagery from an unmanned aerial vehicle in precision agriculture. In: 2013 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). Piscataway (NJ): IEEE; 2013. p. 6723419. https://doi.org/10.1109/igarss.2013.6723419
11. Bendig J, Bolten A, Bareth G. Introducing a low-cost mini-UAV for thermal- and multispectral-imaging. Int Arch Photogramm Remote Sens Spat Inf Sci. 2012;XXXIX-B1:345-50. https://doi.org/10.5194/isprsarchives-xxxix-b1-345-2012
12. Zarco-Tejada PJ, González-Dugo V, Williams LE, Suárez L, Berni JAJ, Goldhamer D, et al. A PRI-based water stress index combining structural and chlorophyll effects: assessment using diurnal narrow-band airborne imagery and the CWSI thermal index. Remote Sens Environ. 2013;138:105–16. https://doi.org/10.1016/j.rse.2013.07.024
13. Anthony D, Elbaum S, Lorenz A, Detweiler C. On crop height estimation with UAVs. In: 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). Piscataway (NJ): IEEE; 2014. p. 4887–92. https://doi.org/10.1109/IROS.2014.6943245
14. Özgüven MM. Determination of sugar beet leaf spot disease level (*Cercospora Beticola* Sacc.) with image processing technique by using drone. Curr Investig Agric Curr Res. 2018;5(3):000214. https://doi.org/10.32474/ciacr.2018.05.000214
15. Wen D, Xing T, You F, Cai C. Measurement of nitrogen content in rice by inversion of hyperspectral reflectance data from an unmanned aerial vehicle. Cienc Rural. 2018;48(6):e20180008. https://doi.org/10.1590/0103-8478cr20180008
16. Schmitz A, Badgujar C, Mansur H, Flippo D, McCornack B, Sharda A. Design of a reconfigurable crop scouting vehicle for row crop navigation: a proof-of-concept study. Sensors. 2022;22(16):6203. https://doi.org/10.3390/s22166203
17. Vardhan PH, Dheepak S, Aditya PT, Arul S. Development of automated aerial pesticide sprayer. Int J Eng Sci Res Technol. 2014;3(4):458–62. https://doi.org/10.15623/ijret.2014.0304151
18. Spoorthi S, Shadaksharappa B, Suraj S, Manasa VK. Freyr drone: pesticide/fertilizers spraying drone - an agricultural approach. In: 2017 2nd International Conference on Computing and Communications Technologies (ICCCT). Piscataway (NJ): IEEE. 2017. p. 119-24. https://doi.org/10.1109/ICCCT2.2017.7972289.
19. Meivel SM, Vasanthapriya A, Maguteeswaran R, Gandhiraj NB, Srinivasan G. Quadcopter UAV based fertilizer and pesticide spraying system. Intl Acad Res J Engineer Scis. 2016.
20. Hall O, Wahab I. The use of drones in the spatial social sciences. Drones. 2021;5(4):112. https://doi.org/10.3390/drones5040112
21. Sarghini F, De Vivo A. Interference analysis of an heavy lift multirotor drone flow field and transported spraying system. Chem Eng Trans. 2017;58:631–6. https://doi.org/10.3303/cet1758106
22. Lee J, Sidle R. Gas-reserves estimation in resource plays. SPE Econ Manag. 2010;2(2):86–91. https://doi.org/10.2118/130102-pa
23. Gharde Y, Singh PK, Dubey RP, Gupta PK. Assessment of yield and economic losses in agriculture due to weeds in India. Crop Prot. 2018;107:12–6. https://doi.org/10.1016/j.cropro.2018.01.007
24. Huang Y, Reddy KN, Fletcher RS, Pennington D. UAV low-altitude remote sensing for precision weed management. Weed Technol. 2018;32(1):1–10. https://doi.org/10.1017/wet.2017.89
25. Dash JP, Pearse GD, Watt MS. UAV multispectral imagery can complement satellite data for monitoring forest health. Remote Sens (Basel). 2018;10(8):1216. https://doi.org/10.3390/rs10081216
26. Ward S, Hensler J, Alsalam B, Gonzalez LF. Autonomous UAVs wildlife detection using thermal imaging, predictive navigation and computer vision. In: 2016 IEEE Aerospace Conference. Piscataway (NJ): IEEE. 2016. p. 1–10. https://doi.org/10.1109/AERO.2016.7500671
27. Zhu H, Lan Y, Wu W, Hoffmann WC, Huang Y, Xue X, et al. Development of a PWM precision spraying controller for unmanned aerial vehicles. J Bionic Eng. 2010;7(3):298–305. https://doi.org/10.1016/S1672-6529(10)60251-x
28. Park S, Ryu D, Fuentes S, Chung H, Hernández-Montes E, O'Connell M. Adaptive estimation of crop water stress in nectarine and peach orchards using high-resolution imagery from an unmanned aerial vehicle (UAV). Remote Sens. 2017;9(8):828. https://doi.org/10.3390/rs9080828
29. Hafeez A, Husain MA, Singh SP, Chauhan A, Khan MT, Kumar N, et al. Implementation of drone technology for farm monitoring & pesticide spraying: a review. Inf Process Agric. 2023;10(1):192-203. https://doi.org/10.1016/j.inpa.2022.02.002
30. Qu T, Li Y, Zhao Q, Yin Y, Wang Y, Li F, et al. Drone-based multispectral remote sensing inversion for typical crop soil moisture under dry farming conditions. Agriculture. 2024;14(3):484. https://doi.org/10.3390/agriculture14030484
31. Mazur P, Gozdowski D, Stępień W, Wójcik-Gront E. Does drone data allow the assessment of phosphorus and potassium in soil based on field experiments with winter rye? Agronomy. 2023;13(2):446. https://doi.org/10.3390/agronomy13020446
32. Mohan M, Richardson G, Gopan G, Aghai MM, Bajaj S, Galgamuwa GAP, et al. UAV-supported forest regeneration: current trends, challenges and implications. Remote Sens (Basel). 2021;13(2):297. https://doi.org/10.3390/rs13020297
33. Pomeroy R. One trillion trees-World Economic Forum launches plan to help nature and the climate. In: World Economic Forum. 2020.
34. Shafi U, Mumtaz R, García-Nieto J, Hassan SA, Zaidi SAR, Iqbal N. Precision agriculture techniques and practices: from considerations to applications. Sensors. 2019;19(17):3796. https://doi.org/10.3390/

s19173796

35. Cheng E. Aerial photography and videography using drones. Berkeley (CA): Peachpit Press; 2015.

36. Shah SA, Lakho GM, Keerio HA, Sattar MN, Hussain G, Mehdi M, et al. Application of drone surveillance for advance agriculture monitoring by android application using convolution neural network. Agronomy. 2023;13(7):1764. https://doi.org/10.3390/agronomy13071764

37. Reyes-Hung L, Soto I, Majumdar AK. Neural network-based stress detection in crop multispectral imagery for precision agriculture. In: 2024 14th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP). Piscataway (NJ): IEEE. 2024. p. 551–6. https://doi.org/10.1109/csndsp60683.2024.10636640

38. Klemas W. Coastal and environmental remote sensing from unmanned aerial vehicles: an overview. J Coast Res. 2015;31(5):1044-56. https://doi.org/10.2112/jcoastres-d-15-00005.1

39. Liang D, Liu W, Zhao Y. Optimal models for plant disease and pest detection using UAV image. Nat Environ Pollut Technol. 2022;21(4):101–10. https://doi.org/10.46488/nept.2022.v21i04.013

40. Cheshkova AF. A review of hyperspectral image analysis techniques for plant disease detection and identification. Vavilovskii Zhurnal Genetiki i Selektsii. 2022;26(1):246–55. https://doi.org/10.18699/vjgb-22-25

41. Lu B, Dao PD, Liu J, He Y, Shang J. Recent advances of hyperspectral imaging technology and applications in agriculture. Remote Sens (Basel). 2020;12(16):2659. https://doi.org/10.3390/rs12162659

42. Guebsi R, Mami S, Chokmani K. Drones in precision agriculture: a comprehensive review of applications, technologies and challenges. Drones. 2024;8(11):686. https://doi.org/10.3390/drones8110686

43. Fikri MR, Candra T, Saptaji K, Noviarini AN, Wardani DA. A review of implementation and challenges of unmanned aerial vehicles for spraying applications and crop monitoring in Indonesia. arXiv. 2023. https://doi.org/10.48550/arXiv.2301.00379

44. Nordin MN, Mat Jusoh MS, Abu Bakar BH, Ahmad MT, Mail MF, Tet Vun C, et al. Study on water distribution of spraying drone by different speed and altitude. Adv Agric Food Res J. 2021;2(2):10–7. https://doi.org/10.36877/aafrj.a0000215

45. Kovalev IV, Kovalev DI, Astanakulov KD, Shaporova ZE, Podoplelova VA, Borovinsky DV. Performance analysis of UAV sprayer application in precision agriculture. Earth and Environmental Science. 2023. p. 012057. https://doi.org/10.1088/1755-1315/1231/1/012057

46. Fritz BK, Hoffmann WC, Bagley WE, Hewitt A. Field scale evaluation of spray drift reduction technologies from ground and aerial application systems. J ASTM Int. 2011;8(5):STP49685S. https://doi.org/10.1520/stp49685s

47. Al-Shareeda MA, Manickam S, Saare MA. Intelligent drone-based IoT technology for smart agriculture system. In: 2022 International Conference on Data Science and Intelligent Computing (ICDSIC). Piscataway (NJ): IEEE. 2022. p. 553–8. https://doi.org/10.1109/ICDSIC56987.2022.10076170

48. Shaw KK, Vimalkumar R. Design and development of a drone for spraying pesticides, fertilizers and disinfectants. Int J Eng Res Technol. 2020;9(5):1089–92.

49. Zhang YL, Lian Q, Zhang W. Design and test of a six-rotor unmanned aerial vehicle (UAV) electrostatic spraying system for crop protection. Int J Agric Biol Eng. 2017;10(6):75–84. https://doi.org/10.25165/j.ijabe.20171006.3460

50. Ali H, Zaheer A, Khan S, Ahmed N, Fayyaz A. A hazard-free framework for aerial distribution of pesticides on agricultural land. Mehran Univ Res J Eng Technol. 2020;39(3):545–62. https://doi.org/10.22581/muet1982.2003.10

51. Yoshida K, Fuzesi I, Suzan M, Nagy L. Measurements of surface contamination of spray equipment with pesticides after various methods of application. J Environ Sci Health B. 1990;25(2):191–209. https://doi.org/10.1080/03601239009372682

52. Zhou Q, Zhang S, Xue X, Cai C, Wang B. Performance evaluation of UAVs in wheat disease control. Agronomy. 2023;13(8):2131. https://doi.org/10.3390/agronomy13082131

53. Ijaz B, Nazeer S, Sajjad M, Nadeem M, Anwar H, Idrees M, et al. Effect of various foliar applied micronutrients (Zn+Fe+Cu+B) on growth and yield of wheat under Faisalabad condition. J Glob Innov Agric Sci. 2023;11(2):49–55. https://doi.org/10.22194/jgias/11.1035

54. Rejeb A, Abdollahi A, Rejeb K, Treiblmaier H. Drones in agriculture: a review and bibliometric analysis. Comput Electron Agric. 2022;198:107017. https://doi.org/10.1016/j.compag.2022.107017

55. Munawir M, Susanta G. Penentuan alternatif lokasi tempat pembuangan akhir (tpa) sampah di kabupaten sidoarjo. AJOSH J Sci Health. 2022;1(11):92. https://doi.org/10.59888/ajosh.v1i11.92

56. Chan YK, Koo VC, Zahisham MZA, Lim KM, Connie T, Lim CS, et al. Design and development of a drone based hyperspectral imaging system. In: 2022 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). Piscataway (NJ): IEEE. 2022. p. 4880-3. https://doi.org/10.1109/IGARSS46834.2022.9884767

57. Rahaman DMM, Baby T, Oczkowski A, Paul M, Zheng L, Schmidtke LM, et al. Grapevine nutritional disorder detection using image processing. In: Ryo Y, editor. Neural Information Processing. Cham (CH): Springer. 2019. p. 473–84. https://doi.org/10.1007/978-3-030-36718-3_42

58. Al-Mulla Y, Al-Ruehelli A. Use of drones and satellite images to assess the health of date palm trees. In: 2020 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). Piscataway (NJ): IEEE. 2020. p. 1089–92. https://doi.org/10.1109/IGARSS39084.2020.9324021

59. Mohite JD, Gauns A, Twarakavi N, Pappula S. Evaluating the capabilities of Sentinel-2 and Tetracam RGB+3 for multi-temporal detection of thrips on capsicum. Int Arch Photogramm Remote Sens Spat Inf Sci. 2018;XLII-5/W1:407–14. https://doi.org/10.5194/isprs-archives-XLII-5-W1-407-2018

60. Suzuki Y, Okamoto H, Kataoka T. Image segmentation between crop and weed using hyperspectral imaging for weed detection in soybean field. Environ Control Biol. 2008;46(3):163–71. https://doi.org/10.2525/ecb.46.163

61. Okamoto H, Murata T, Kataoka T, Hata SI. Plant classification for weed detection using hyperspectral imaging with wavelet analysis. Weed Biol Manag. 2007;7(1):33-40. https://doi.org/10.1111/j.1445-6664.2006.00234.x

62. Wendel A, Underwood J. Self-supervised weed detection in vegetable crops using ground based hyperspectral imaging. In: 2016 IEEE International Conference on Robotics and Automation (ICRA). Piscataway (NJ): IEEE. 2016. p. 488-94. https://doi.org/10.1109/ICRA.2016.7487717

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

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.