

Precision Farming Technologies: A Comprehensive Review of Drone and Sensor Applications for Sustainable Crop Management

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ABSTRACT

The agriculture sector is undergoing a technological revolution in order to cope with various emerging challenges like food insecurity, resource scarcity, climate variability, and environmental degradation. Traditional agricultural systems based on random usage of agricultural inputs and laborious farming practices are becoming less sustainable in the face of changes in climatic and socio-economic environments. Precision agriculture is defined as a technology-based and site-specific approach in agriculture, which is based on the application of digital technologies for crop cultivation while making the optimal use of natural resources. Unmanned aerial vehicles (drones) and intelligent sensor systems are some of the modern agricultural technologies. Multispectral, hyperspectral, thermal and RGB imaging technologies allow drones to instantly assess plant health, incidence of pests and diseases, nutrient deficiencies, weed problems, watering needs, and yield estimates. At the same time, various sensors in soils and environment measure important parameters such as soil moisture, nutrient content, temperatures, humidity, soil pH, and electrical conductivity. Combining all the above technologies with GIS, GPS, AI, ML, and IoT provides precise and automated agricultural interventions tailored to individual plots that increase production, decrease costs, optimize resource use, and minimize negative impacts on the environment. In this review paper, an in-depth evaluation of the concepts behind precision agriculture, types and functioning of drone technology and sensors, usage of drones in agriculture, advantages of drones in agriculture in terms of economy and environment, limitations of using drones in agriculture, and future directions for research are done. In addition to that, current status, policies related to precision agriculture, and adoption of precision agriculture in India and elsewhere are elaborated upon.

Keywords: Precision farming, drones, sensors, crop management, UAV, IoT, smart agriculture, GIS

INTRODUCTION

The agricultural sector has undergone a profound transformation over the past few decades, evolving from labour-intensive conventional farming to highly mechanized and digitally enabled production systems. This transition has been driven by rapid population growth, increasing food demand, shrinking natural resources, and the urgent need to achieve sustainable agricultural development. According to the Food and Agriculture Organization (FAO), global food production must increase by nearly 50–60% by 2050 to feed a projected population approaching 9.7 billion. Achieving this target is becoming increasingly challenging because of climate change, declining soil fertility, water scarcity, land degradation, biodiversity loss, and the increasing

incidence of pests and diseases. These challenges necessitate the adoption of innovative technologies capable of improving resource-use efficiency while minimizing environmental impacts. Conventional agricultural management generally relies on uniform applications of irrigation water, fertilizers, and pesticides across entire fields, despite considerable spatial variability in soil properties, nutrient availability, moisture status, and crop growth. Such blanket applications frequently result in excessive input use, nutrient losses, reduced fertilizer-use efficiency, increased production costs, environmental pollution, and suboptimal crop productivity. Precision agriculture (PA), also referred to as precision farming, has emerged as an effective approach to overcome these limitations by enabling site-specific crop management. Precision agriculture integrates advanced sensing, positioning, and decision-support technologies to monitor, measure, analyse, and manage spatial and temporal variability within agricultural fields, ensuring that the right input is applied at the right place, at the right time, and in the right quantity (Zhang et al., 2002). Studies have shown that precision farming can reduce fertilizer and pesticide use by approximately 15–30%, decrease irrigation water consumption by 20–40%, and simultaneously improve crop productivity and farm profitability while reducing environmental footprints. Among the core technologies supporting precision agriculture, unmanned aerial vehicles (UAVs), commonly known as drones, and intelligent sensor systems have become indispensable tools for real-time crop monitoring and decision-making. Modern agricultural drones equipped with RGB, multispectral, hyperspectral, thermal, and LiDAR sensors can rapidly survey large agricultural fields, generate high-resolution imagery with centimetre-level spatial resolution, detect nutrient deficiencies, identify weed infestations, monitor crop stress, estimate biomass, assess plant health, support irrigation scheduling, and perform precision spraying. Depending on payload and battery capacity, most commercial multirotor agricultural drones operate for approximately 20–40 minutes per flight and typically cover 10–20 ha per mission, whereas fixed-wing UAVs can survey substantially larger areas. Ground-based sensor networks continuously monitor soil moisture, temperature, electrical conductivity, pH, nutrient status, humidity, and other environmental parameters, enabling continuous assessment of crop and soil conditions. When integrated with Geographic Information Systems (GIS), Global Positioning System (GPS), Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT), these technologies facilitate automated, data-driven, and site-specific farm management, thereby improving input-use efficiency and supporting climate-smart agriculture (Sharma et al., 2021). Despite their considerable potential, widespread adoption of drones and sensor-based precision agriculture remains constrained by several technical, economic, and regulatory challenges. High initial investment costs for UAV platforms, advanced sensors, and software remain a major obstacle, particularly for smallholder farmers. Additional limitations include restricted battery endurance, limited payload capacity, dependence on favourable weather conditions, the need for skilled operators and data-processing expertise, concerns regarding data management and cybersecurity, and inadequate rural digital infrastructure. In developing countries, particularly India, adoption is further hindered by fragmented and small landholdings, limited access to credit, insufficient awareness and technical training, poor availability of maintenance services, and regulatory requirements governing UAV operation under the Directorate General of Civil Aviation (DGCA). These structural barriers significantly influence the scalability and economic viability of precision agriculture technologies and therefore require careful consideration alongside their technical advantages. Given the rapid advancement of digital agriculture and the increasing emphasis on sustainable and climate-resilient farming systems, a comprehensive understanding of drones and sensor technologies has become essential for researchers, policymakers, extension professionals, technology developers, and farmers. Therefore, this review critically examines the principles and components of precision agriculture, the operational capabilities of agricultural drones, the various sensor technologies used in crop and soil management, and their applications in site-specific farming. In addition, the review evaluates the operational limitations of drone-based agriculture, discusses the socio-economic and regulatory barriers affecting large-scale adoption—particularly in the Indian context and highlights future research directions and technological innovations required to accelerate the transition towards intelligent, sustainable, and data-driven agricultural systems

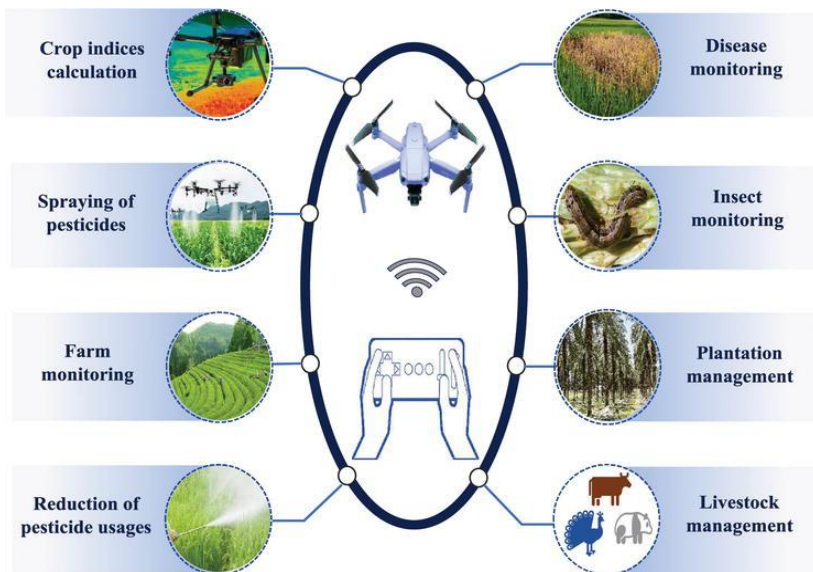


Figure.1 Representing the applications of drones in Agriculture

Concept of Precision Farming

Precision farming, otherwise known as Precision Agriculture (PA), Smart Farming, or Digital Agriculture, is an innovative farm management technique that makes use of information and communication technologies to observe spatial and temporal variability within agricultural land and improve crop production (Gebbers & Adamchuk, 2010). In contrast to traditional farming methods that use agricultural inputs uniformly for an entire field, precision farming appreciates the fact that there exist variations within a field in terms of soil composition, crop development, nutrients, moisture conditions, and presence of pests. By detecting and managing these variations, precision farming allows for targeted crop management that results in improved productivity and efficient use of resources. The core idea of precision farming is captured in the saying that "it is all about doing the right thing, in the right place, at the right time, and in the right amount." It means that necessary inputs like water, fertilizers, pesticides, and seeds will be used as per the requirement of particular spots within a field. This allows maximum input efficiency, while keeping costs low and minimizing negative effects on the environment. Advanced instruments like drones, satellite technology, sensors, Global Positioning System (GPS), Geographic Information System (GIS), and remote sensing are used to gather information. This information is then analyzed through AI, ML, and predictive models to produce recommendations regarding irrigation scheduling, nutrients management, pest and diseases management, and crop yield prediction. Automation and Variable Rate Application (VRA) technology put the recommendations into practice with accuracy and very little human interference. Through intelligent information gathering and analysis and decision-making, precision agriculture increases productivity, increases efficiency in the use of resources, saves water, fertilizers, pesticides, and energy, and also reduces pollution. As a result, it has become an important element of climate-smart and sustainable agriculture.

Components of Precision Agriculture

The adoption of precision agriculture has helped climate-smart and sustainable agriculture through the incorporation of digital technologies that help achieve precise, evidence-based and site-specific crop production. Precision agriculture involves using geospatial technologies, sensing systems, communication technologies and intelligent data analysis to monitor crop and soil variability to achieve optimal use of agricultural inputs (Zhang et al., 2002). The major technological innovations of precision agriculture include Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, IoT, and Artificial Intelligence (AI). Each of the above-listed technologies plays an important role in increasing farm productivity and improving efficiency in the use of resources. Geographic Information System (GIS) is a computer-based technology for collection, storage, analysis, and visualization of geographic data about agricultural fields. GIS allows preparing digital

maps, analysis of soil conditions, monitoring of crops performance, measuring of yield variability, and planning of land use among other tasks. The Global Positioning System (GPS) provides extremely precise geographic coordinates that allow for accurate field activities. GPS is widely used for guiding the tractor, self-driving equipment, drones, field mapping, soil sampling, and spraying applications. Precise positioning prevents overlaps and skips when performing the field activities, thus helps to save inputs, minimize fuel consumption, and decrease operating expenses. Remote sensing is an equally important aspect of precision farming which means gathering information about the crops and soil without any physical interaction with them. Information obtained via satellites, UAVs/drones, and ground sensors provides valuable insight into the state of plants, crop health and vegetation indexes, soil moisture, deficiencies in nutrients, pests and diseases presence, and water stress. This way, potential issues with the crops can be detected timely and management actions can be taken to improve yields. The Internet of Things (IoT) integrates agricultural devices, sensors, and machinery using internet communication systems, making it possible to monitor field conditions continuously (Ray, 2017). The Internet of Things enables the gathering and transfer of soil moisture, temperature, humidity, nutrient levels, and weather information to cloud servers so that farmers can monitor their farms remotely and automate irrigation, fertilization, and other activities. The use of such technology increases the efficiency of resource management and enables automation of decision-making processes. Another technology which contributes to the improvement of precision agriculture is Artificial Intelligence (AI), which involves processing of large volumes of agricultural data and creation of intelligent suggestions concerning farm management (Liakos et al., 2018). Such applications can help farmers to predict pests and diseases, estimate crop yields, optimize irrigation and fertilizers use, detect weeds, and make decisions. Combining AI with geographic information systems, global positioning system, remote sensing, unmanned aerial vehicles, and Internet of Things allows creating actionable knowledge from field data.

Role of Drones in Agriculture

Drones, also referred to as Unmanned Aerial Vehicles (UAVs), refer to remote control or automated aircraft used to conduct farm operations without a pilot present inside (Hunt et al., 2010). Drones have proved to be essential tools for precise and quick field surveys in modern precision agriculture. Modern agricultural drones have state-of-the-art technology features such as high-resolution RGB cameras, Global Positioning Systems (GPS), thermal imaging cameras, multispectral cameras, and spray systems. Such technology allows for collecting detailed spatial information as well as the health status of crops. This technology enables drones to swiftly survey large agricultural fields, create high-resolution images, as well as monitor crop growth, soil status, nutrient deficiency, pest and disease infections, weeds spread, irrigation needs, and overall field variation (Sharma et al., 2021). The timely data obtained from drone applications enable the making of well-informed decisions, efficient site-specific crop management, effective use of agricultural inputs, and optimization of resource utilization. In essence, drone technology is an important feature of precision agriculture today.

Types of Agricultural Drones

There are three types of agricultural drones: fixed-wing, rotary-wing, and hybrid drones. The drones vary depending on design, flight behavior, and functionality (Hunt et al., 2010). There are several pros of each drone that make farmers choose one of the mentioned types of drones based on the size of the farm, terrain, and intended purpose of the drones. Fixed-wing drones are similar to regular aircrafts and are designed to fly for long periods of time and cover vast areas. They have higher speed of flying and can cover large agricultural territories in one flight, which makes them very useful for large farms, crop monitoring, land surveying, and field mapping. High-quality geospatial data generation allows for improving the precision in crop management and resource allocation. However, fixed-wing drones normally need a runway or launching system for taking off and landing and have limited manoeuvrability, which means that they cannot be used effectively in confined spaces and precision spraying. This technology proves to be very efficient when it comes to specific agricultural activities that require precision. However, the limited flight duration and smaller coverage of these types of drones are a disadvantage in cases of field surveying on a large scale. The hybrid drone incorporates all the best qualities of the fixed and rotary wing drones, as it includes VTOL technology along with long-distance flight ability (Hunt

et al., 2010). As a result, this type of drone can cover great distances in an effective way and at the same time has the advantage of flying in the field where runways cannot be found.

Applications of Drones in Crop Management

Drones are becoming an important part of precision agriculture due to the provision of fast, precise, and high-resolution information, which helps manage crops and fields in an effective manner. With the help of their sophisticated imaging technology and through the integration with Artificial Intelligence (AI) and Geographic Information Systems (GIS), drones can facilitate different agricultural processes which lead to increased productivity and better utilization of resources. One of the main uses of drones includes crop monitoring wherein high-resolution RGB, multispectral, and thermal images are obtained in order to determine the health of the crops and detect water stress, nutrient deficiency, pests, and diseases at an early stage (Sharma et al., 2021). Early detection helps prevent crop damage and loss and increases the productivity of farms. Drones are also widely employed for precision spraying of pesticides, herbicides, and liquid fertilizers in order to reduce the use of chemicals, prevent spray drift, save time, decrease the cost of labor, and increase the efficiency of crop protection practices (Sharma et al., 2021). Thermal imagery from drones aids in identifying moisture-stressed spots in the fields for better scheduling of irrigation, avoiding over-irrigation, and conservation of water resources. Drones' thermal imagery is widely used in detecting weeds in which image processing technologies help distinguish between crops and weeds for herbicides' site-specific application (Davis et al., 2020). In addition, yield prediction is done through the incorporation of drone imagery with algorithms of artificial intelligence, where the information on crop biomass, plant population, canopy structure, and plant development helps in making a good estimate of crop yield potential (Liakos et al., 2018). One of the uses of drone technology is in the mapping of soils and fields in which drones help make orthomosaic images, 3D terrain models, maps of soil variability, and drainage maps prior to planting (Liakos et al., 2018). The maps help the farmers in making decisions about land preparation, irrigation scheduling, fertilizer management, and variable rate input application.

Sensors Used in Precision Farming

In precision agriculture, sensors are very important since they sense changes in the environment and convert them into measurable signals. They give an accurate measurement of soil, crops, and atmosphere, allowing the farmer to manage resources properly. There are different kinds of sensors used in agriculture. The soil moisture sensors detect the level of moisture in the soil, allowing farmers to schedule irrigation, save water, and reduce stress caused by water shortage in the crops. The nutrient sensors detect the level of available nutrients in the soil, including N, P, and K, allowing proper fertilization and reducing nutrients wastage. The temperature sensors detect soil and air temperatures since they play an important role in the growth of plants, germination of seeds, and infection by diseases. Humidity sensors measure the atmospheric moisture content and they are mostly used in greenhouses and disease prediction. Optical sensors measure the reflection of light from crop canopy to estimate plant health and chlorophyll levels, and to calculate vegetation index for monitoring crops' growth. The thermal sensors sense differences in temperature among the plants, thereby helping to determine any water stress, any outbreak of diseases, and other physiological disturbances in the crops. Biosensors belong to the higher level of sensors that are used for detecting diseases quickly, detecting pathogens, and assessing the quality of food items. All these sensing techniques help us understand the exact condition of agriculture.

Applications of Sensors in Crop Management

Sensor technology is vital in precision agriculture, as it allows continuous monitoring of environmental and field conditions. Thus, farm management decisions are made rationally and site-specifically. One of the most important applications of sensors is smart irrigation, where soil moisture sensors control automatic irrigation depending on the needs of plants, saving water and increasing the effectiveness of plant growth (Patel & Kumar, 2021). The sensors for monitoring the environment are also vital in detecting plant diseases, as well as forecasting them depending on such conditions as humidity and temperature, which are favorable for plant disease development. For instance, high humidity can cause fungal diseases; thus, preventive measures can be taken by

farmers (Williams & Zhao, 2018). In fertilizer management, sensors assess the availability of nutrients in the soil and, therefore, allow applying fertilizers appropriately, minimizing nutrient losses. Furthermore, sensors are widely used in greenhouse monitoring, when all environmental conditions, including humidity, temperature, and light intensity, are controlled.

Integration of Drones and Sensors

The current era of precision agriculture combines drone technology, sensor network, cloud computing, and Artificial Intelligence (AI) to develop an intelligent agriculture system. In the combined application, sensors in the field continue collecting real-time data related to soil moisture level, soil nutrition status, temperature, humidity, and other environment parameters while drones are used to collect high-resolution aerial pictures to determine crop status, variability, and incidence of pests and diseases in the field. Data collected through sensors and drone technology are sent to the cloud, where AI-based algorithms analyze the data, determine patterns and generate recommendations for irrigation, fertilizer application, pest management, and other field activities. Recommendations generated through AI analysis are conveyed to farmers for making informed decisions about field operations. The integration of drone technology, sensor network, and AI improves precision in agricultural activities, increases automation, boosts farm productivity and promotes efficient use of resources.

Advantages of Precision Farming

The application of precision agriculture is highly beneficial from the economic, environmental, and socio-economic point of views as far as the efficiency and productivity of the agricultural practices are concerned. In terms of economy, precision agriculture leads to better crop yield using specific location-based techniques while saving on labor requirements and making the best use of the necessary inputs like water, fertilizers, pesticides, and energy. The better utilization of resources helps in lowering the costs of production, increases the efficiency of input utilization, and ultimately results in profitability for the farmers. As far as the environment is concerned, precision agriculture avoids excessive use of agrochemicals through the specific application of chemicals depending upon the needs of crops and helps in avoiding soil, water, and air pollution. It further helps in conserving water through better irrigation management and encourages sustainable agriculture by making minimum wastage of resources and preventing the degradation of natural ecosystems. Socio-economically, the adoption of precision technologies ensures safety of farmers by avoiding their direct contact with pesticides and dangerous agricultural activities, reduces physical labor through automation, and ultimately makes contribution towards ensuring food security by improving agricultural output.

Limitations and Challenges

While precision agriculture has many benefits, there are some obstacles to it, which make it difficult to adopt. First of all, the high cost of drones, sensors, and other precision technologies make them unaffordable for small and marginal farmers (Gomez & Martinez, 2022). To be used effectively, precision technologies require certain technical knowledge and expertise. Besides, limited battery power of drones decreases their flight time, while low quality of internet connection in rural areas is a barrier for IoT devices. Moreover, a vast amount of data obtained in agriculture needs effective management. Weather conditions like rain, wind, and fog complicate the work of drones.

Status of Precision Agriculture in India

India is gradually embracing the latest technologies in precision agriculture to boost agricultural output, efficient resource use, and sustainability (ICAR, 2020). Various government programs like agricultural drones subsidy, smart irrigation promotion, and Digital Agriculture Mission are promoting the adoption of modern agricultural technologies. Moreover, there is growing innovation by agricultural colleges, research organizations, and startups in providing AI-powered advisory services, spraying drones, and smart irrigation solutions. This technology is gradually being adopted in key crops like rice, wheat, cotton, and other horticultural crops due to their role in boosting the efficiency of inputs use, minimizing cost of production, and improving crop yield.

Future Potential of Precision Agriculture

The future of precision agriculture will involve the utilization of smart digital technologies, which will make agriculture more intelligent, automated, and sustainable. According to Liakos et al., (2018), Artificial Intelligence (AI) will increase the effectiveness of disease detection, crop production estimates, and automated decision making on farms. Drones and robots will increasingly be used to undertake operations such as monitoring of crops, harvesting, weed removal, and spraying in a highly autonomous manner. The development of 5G technology will provide faster real-time data exchange and enhanced communication between drones and IoT devices.

CONCLUSION

Although there is vast potential in the usage of drones and sensors for precision agriculture for improving resource-use efficiency, increasing crop productivity, and ensuring sustainability, the large-scale adoption of this technology faces a number of hurdles. These include low battery life, limitations in terms of carrying payload, higher cost of the equipment, data-processing needs, and operator skill. In addition, in the case of India, there are other constraints like fragmentation of small holder farms, insufficient digital infrastructure in rural areas, lack of technical knowledge, and DGCA regulations that hinder the process of adoption. The overcoming of these technical, infrastructural, and policy hurdles will play a crucial role in promoting precision agriculture in future.

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Author's contribution

Shruti and NK collected the review of literature, conceptualized and prepared the manuscript as part of research work under the supervision of SRM and BKP. SRM guided the overall structure, provided critical reviews and supervised the review process.

Compliance with ethical standards

Conflict of Interest: The authors assure and clarify that there are no known conflicts of interest occurs which could influence the research pointed in this review. This work has been presented and conducted independently without financial or personal relationships that could be perceived as biasing the content.

Ethical issues: None

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