The Use of Drones in Precision Agriculture

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ABSTRACT
Precision agriculture has revolutionized the contemporary style of farming using drones or unmanned aerial vehicles (UAVs) to assist farmers in decision-making and management of resources basing on the data. Drones help farmers to see the data of the state of crop and the heterogeneity of soil in real-time and in a high-resolution state, as well as the irrigation requirements, pests' number, and yield mapping. The technology supports site specific management practices that enhances productivity, decreases resources and supports environmental sustainability. Although the potential of drones is enormous, issues like high initial prices, legal issues, short battery duration, and the necessity to employ professional pilots are all enormous impediments to a large-scale usage. This paper will discuss the historical perspective, the principles of operation, uses, pros, and cons of drones in the field of precision agriculture and the future outlook of the drone technology. It also offers a vivid understanding of how drone technology may right the agricultural practices and increase food security in the twenty-first century and aid the sustainable agricultural expansion by using case studies and real-life applications.
KeyWords: sustainability, food security, drones, UAVs, precision agriculture, crop monitoring.

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INTRODUCTION

Agriculture is one of the oldest human activity that exist in the existence and there is no doubt in the twenty first century agriculture is facing the more challenges than ever before, including but not limited to climate change, population growth, degradation of the soil, and the escalating demand of sustainable food production (Gebbers & Adamchuk, 2010). Current farming methods which were previously successful are not adequate enough to supply the world population which is estimated at 9.7 billion by the year 2050 (United Nations, 2019). This has led to an increased use of innovative technologies in the agricultural sector eg precision agriculture to optimize the usage of resources and productivity.

Site-specific crop management or precision agriculture is the application of the latest technologies, such as remote sensing and geographic information system (GIS) and automation, to monitor variability in the field and to optimize inputs (Mulla, 2013). Among these technologies, the most promising of them is the usage of drones or unmanned aerial vehicles (UAVs) due to their flexibility, affordability and the ability to gather high-resolution data within a limited timeframe (Zhang and Kovacs, 2012).

Drones have the capability of revolutionizing agriculture by providing the farmer with real time and detailed data on crop health, soil heterogeneity, pests and water stress (Hunt et al., 2010). Drones are equipped with sensors like multispectral, hyperspectral and thermal cameras and therefore have the ability to identify subtle changes of the health of the vegetation in the early stages, before the naked eye. This helps the farmers to only use fertilizers, pesticides, and water where they are required the most to stop any wastage and land erosions (Colomina & Molina, 2014). In addition, the drones are increasingly getting application in spraying on crops, planting, and estimation of their yield, which is very important in the current farming system of precision farming.

Their application in agriculture has not been bereft of challenges even with their potential as a revolution. High cost of adoption, data processing requirement, short length of flight and stringent aviation controls are issues to limit further adoption especially in low- and middle-income nations (Tsouros et al., 2019). Also the privacy of the data and lack of technological knowledge in rural areas, misuse of drones also create ethical and social concerns.

This paper seeks to give a general review on the role of drone in precision agriculture regarding their history, technological background, uses, advantages, disadvantages and future projections. Case studies and international experiences are also given to show how drones are being incorporated in the agricultural system in every corners of the world. Finally, at the end of the paper it is concluded that in general, drones with appropriate control and overall use have an unimaginable potential to help solve the problems of a contemporary farming and contribute in some way to the overall food abundance of the globe and helping to build a sustainable agricultural system.

Historical Development of Drones in Agriculture

Early History of Drone Technology

The history of drones, or more formally known as unmanned aerial vehicles (UAVs), goes back as far as the usage of drones in military situations during World War I and II, where drones were created primarily for surveillance and target practice (Austin, 2010). These early unmanned aerial vehicles were the foundation upon which drones were used in civilian assorted applications. During the late 20th century, progresses in light materials, battery systems, and navigation technologies enabled drones to move away from defense industries into business sectors, such as agriculture (Colomina & Molina, 2014).

Agriculture, traditionally human-dependent and labor-intensive, was a natural candidate for UAV use. Farmers have historically made use of terrestrial approaches to crop survey, pest management, and irrigation scheduling, which were time-consuming and subject to errors. The development of drones promised to deliver high-quality aerial views and auto-acquisition data, offsetting the limitations of human-centered practices (Tsouros et al., 2019).

Early Experimentations with Agricultural Utilization

History Drones started being used in the agricultural sector in the late 1980s and early 1990s in Japan. One of the earlier mass market applications of drones was a small helicopter UAV called Yamaha RMAX, which was launched as a pilot project to spray rice paddies in the air (Huang et al., 2013). High labor cost and small agricultural land area in Japan offered a right environment to experiment UAV technology in agriculture. This groundbreaking study demonstrated that drones were capable of radically decreasing the intensity of work and improving the precision of the utilization of pesticides and fertilizers.

In other parts of the world, the initial efforts were more scientific with research institutions and universities experimenting with drones to inspect crops and control the environment. The more sophisticated drones emerged when the GPS technology gained popularity in the early 2000s, and autonomous flight patterns, as well as real-time delivery of the information became an option (Zhang and Kovacs, 2012).

The Emergence of Precision Agriculture and Drone Uptake

Precision agriculture, a farm management approach that uses technology like geographic information systems (GIS), remote sensing, and unmanned aerial vehicles (UAVs) to optimize production and sustainability, emerged in the 21st century, marking a turning point.. Precision agriculture put "site-specific management" center stage, wherein inputs of water, fertilizers, and pesticides were used only where required (Gebbers & Adamchuk, 2010). Drones became a significant piece of equipment for this paradigm since they can help farmers collect information from the sky regarding the condition of their crop, soil quality, and field heterogeneity with unprecedented precision.

By the mid-2010s, the development of drone technology became accessible to a much larger market due to the falling prices of drone hardware, availability of flight software on open source platforms, and advances in light-weight sensors (e.g., multispectral and thermal sensors). They revolutionized drones from being a test object to being a useful part of the farm (Patricio & Rieder, 2018). UAVs had been used to do things like scouting crops, tracking livestock, irrigation planning and yield forecasting in countries like North America, Europe and Asia more frequently.

Regulatory and Technological Milestones

The use of drones in agriculture was also followed by changes to the regulation frameworks. At first, operations of drones were limited by strict air laws in most countries with only experiment with the use of drones allowed. However, with the agricultural benefits coming into view, particular guidelines for the commercial use of drones were drafted by the governments, particularly the United States and European Union (FAA, 2016). The regulatory changes hastened the commercialization of drones in agriculture.Parallel to the above advancements, artificial intelligence (AI) and machine learning (ML) integration contributed to increasing the analytical capabilities of drones. No longer just taking aerial photographs, drones were able to now analyze data to determine crop diseases, estimate biomass, or establish nutrient deficiencies in real time (Liakos et al., 2018 This change grew from manual interpretation of drone photos to full automatic decision-support systems.

Global Expansion of Agricultural Drones

By the later 2010s and early 2020s, drones spread across the world, both on large commercial farms in developed economies and smallholder farms in developing economies. In Africa, by way of example, drones were utilized to map farmland, identify locust outbreaks, and measure post-harvest losses (Clarke & Banga, 2020). Government programs and initiatives in India greatly encouraged the use of UAVs as a rudiment to the modernization of agriculture and minimum use of manual based methods by farmers (Sharma et al., 2021).

Present Status and Future Directions

Nowadays, drones are a part of the digital agriculture and are combined regularly with other technologies, for example satellite data, those measuring IoT with the structure of the soil and self-driving tractors. They have progressed past the simple use of aerial photography to the advanced use of variable rate use and 3D crop modeling. The development of drones in agriculture is an ongoing process, which is supported by technological changes, regulatory changes, and the trend of promoting sustainable agricultural systems worldwide.

Drones will be at the heart of solving agricultural problems such as climate change, food and resource shortage and will, therefore, be at the heart of precision agriculture as we enter the 21st century.

Principles and Technologies of Drone-Based Pre-Cise Agriculture

Precision agriculture with drones is a combination of unmanned aerial vehicles (UAVs) and the latest sensing, imaging, and data processing technology used to allow optimization of the effectiveness of the management of the farm. Drones have revolutionized the technique farmers use to scan, measure, and control their farms after the basic principles of precision agriculture, namely those of efficiency, accuracy, sustainability, and decision support (Zhang and Kovacs, 2012). The next part of this paper describes the key principles of drone use in agriculture and technologies that allow such practice.

Drones and the Principle of Precision Agriculture

The search for precision in terms of both Space and Time

One of the typical principles of drone use in agriculture is spatially explicit data collection. Drones are capable of generating centimetre resolution maps of the fields they fly that enable farmers to map intra-field variability in soil, water, and crop health (Colomina & Molina, 2014). Drones can also be used for temporal surveillance to give repeated measurements all through the growing season to track plant growth and detect anomalies.

Data-Driven Decision Making

The field of agriculture is being converted into a process which has been turned into data-driven, and decisions are made on facts, rather than assumptions. With the integration of the data from drones into Farm Management Information Systems (FMIS) and Geographic Information Systems (GIS), farmers are able to apply site-specific interventions such as the application of fertilizers, pesticides, or irrigation based only where required (Mulla, 2013).

Sustainability and Resource Optimization

Precise drone applications are such that they reduce the excessive use of agrochemicals and water and thereby curtail environmental impacts without any loss of yields. For example, spraying drones in aerial spraying can reduce pesticide drift compared to traditional methods while maintaining efficiency as well as safeguarding the environment (Shamshiri et al., 2018).

Automation and Real-Time Monitoring

The second paradigm is becoming more and more mechanized in agricultural processes. Most drones already have the ability to fly autonomously with pre-planned routes based on programmed flight plans, and the images can be livestreamed to allow real-time scouting of the field and faster response to issues (pest infestation or water stress) (Tripicchio et al., 2015).

Underpinning Technologies for drone based Precision Agriculture

Agricultural drones work based on a combination of aerial platform, sensor, imaging, communication and data analysis software to be successful.

Drone Platforms

Drones are used in agriculture in two types:

Fixed-Wing Drones: Are able to cover large quantities of land effectively and efficiently. They are applicable in surveying of large farms and the generation of orthomosaic maps**.**

Multirotor Drones: Have increased maneuvering and hovering functionality, and are the most appropriate type to perform local work, such as particular spraying, close crop surveillance, and soil sampling (Tsouros et al., 2019).

Sensors and Imaging Technologies.

It is the sensors that are attached to drones, which enable precision agriculture applications:

RGB Cameras: Record ordinary visual imagery, which can be utilized for simple crop monitoring and growth documentation.

Multispectral Sensors: Measure specific bands of light beyond the visible spectrum such as near-infrared (NIR) to compute vegetation indices such as NDVI (Normalized Difference Vegetation Index) which can be used to monitor the health of plants (Hunt et al., 2010).

Hyperspectral Sensors: This sensor measures hundreds of broad spectral bands to detect the stress of crops, disease or nutrient deficiencies on crops.

Thermal Cameras: Measures the variations in surface temperature, which can be used to signal about the need to irrigate, water stress, or even track livestock (Primicerio et al., 2012).

LiDAR (Light Detection and Ranging): Provides 3D terrain images that are of great importance in the soil erosion study as well as in drainage survey and field drainage (Wallace et al., 2012).

Communication and Data Transmission

The current drones in use in the farms have wireless communication capabilities, such as Wi-Fi, 4G/5G, and satellite connections. The latter enable drones to relay data in real-time to ground stations or cloud systems, where AI algorithms analyze the data to produce actionable data (Tokekar et al., 2016).

Data Analytics and AI Integration

The data that is being gathered from the drones actually uses advancedmachine learning and artificial intelligence software to analyze the data. AI is capable of detecting plant diseases, types of the weeds, yield estimation and predicting the time of harvest with accuracy. Coupled with cloud computing, a combination of the two enables large farms to store and process a lot of agricultural information effectively (Kamilaris and Prenafeta-Boldu, 2018).

Drone Spraying Systems

Apart from the monitoring, drones also carry precision spraying systems. The systems enable drones to spray pesticides, herbicides and fertilizers directly on target spots, trying to minimize the input cost as well as risk to the environment. Smart spraying systems have real-time sensors to control the droplet size and the rate of spraying (Qin et al., 2018).

Integration with Other Precision Agriculture Tools

Drones are not used in solitude very often.They belong to a massive ecosystem of precision agriculture technology, which is comprised of:

Satellite Imaging: Data of Macro level is compared with the data of drones that allows the analysis of micro level.

IoT Sensors: Ground sensors will sense the soil temperature, moisture, and concentration of nutrients and, once again, as compared to drone data, will provide more precise outcomes.

Robotics and Self-Operating Equipment: Drone data goes into robotic planting machines, harvests and sprinkler irrigation systems...

Advantages of Drone Technologies in Agriculture.

- Real-time, high-resolution monitoring of fields.
- Lower input costs due to precise application of inputs.
- Early disease and pest detection in crops.
- Better yield forecasting and resource allocation.
- Environmental sustainability through reduced chemical overuse.

Technical Limitations and Challenges

There are some technical challenges to drone technologies:

Short battery life limits the hours of flying.

- Some countries have rules that limit drone flying.
- Investment in advanced sensors in the work capital.
- Professional skills needed to interpret complex data output.

Crop Management and Monitoring by use of Drones.

Drones in farming have also led to less time required to scan, inspect and manage crops at both the micro level and macro level of crops. High-quality sensors, cameras, and software can enable drones to provide high-definition and real-time data to make timely decisions, add efficiency, and optimize resource allocation. Drones have been used in various applications in crop monitoring and management, among them are in monitoring of the plant health, monitoring its growth, identifying stress, estimating yield and managing precision input application. These are the applications that are elaborated in this section.

Remote Sensing and Vegetation Indices

Collecting remote sensing data became the most important task that the drones have done in the agricultural sector. The drones utilize multispectral, hyperspectral and thermal cameras to obtain crop reflectance at different wavelengths of light. It is this body of data that get manipulated to generate vegetation indices like the Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDRE) and Soil-Adjusted Vegetation Index (SAVI) (Hunt et al. 2018).

NDVI Mapping NDVI, in this respect, allows farmers to defined the level of plant health and detection of plant stress in the first stage based on the content of chlorophyll and the density of the canopy.

Thermal Imaging: Thermal imaging cameras mounted on a drone can also detect water stress in the plants as reflected on the leaf surface temperature.

Early Disease and Pest Detection: Spectral analysis can be used to detect the changing spectral patterns of leaf reflectance which are correlated with fungal diseases or insect infestations and which indicate varied nutrient imbalances and actions can be taken before the damage is obvious.

Remote sensing with drone therefore makes it possible to perform an active crop health management without the need of expensive laboratory diagnostics.

Phenotyping and Crop Growth Monitoring

Monitoring of crop growth stage is overwhelming where farmers are now working with drones that are capable of providing more accurate information on a large field area as compared to traditional ground scouting.

Growth Stage Analysis: Drones are able to measure the rate of germination, growth height, canopy cover, and flowering.

High-Throughput Phenotyping: According to Aurus and Kefauver (2018), drones provide a non-destructive method for data acquisition, such as biomass accumulation, canopy structure and leaf area index for phenotypic measurements. Temporal Analysis: Repetitive flights over the same fields enable the creation of time series data and provide information on crop dynamics for varying environmental and management regimes. The tool is not only good for farmers but also useful for agricultural scientist who is working on a breeding and crop improvement program.

Nutrient and Irrigation Management

Precision agriculture is based on optimizing application of nutrients and irrigation, and information which is actionable from drones to assist with intervention at a site-specific level.

Nutrient Deficiency Detection: Multispectral imagery can help to identify areas with deficits in nitrogen, phosphorus, or potassium permitting that operation of variable rate fertilizing.

Precision Irrigation: Thermal sensors are used to monitor water stress and soil moisture heterogeneity inside fields, which is used to plan irrigation. This reduces wastage of water and produces high water use efficiency.

Variable-Rate Application Maps: Data from the use of drones could be combined with precision equipment to implement variable rate application of water and fertilizer.

It has been proved from studies that precision irrigation using drone data can increase water use efficiency by 20-40% with the same or even higher yield maintenance (Zarco-Tejada et al., 2019).

Pest and Disease Monitoring

Diseases and pest outbreak cause great losses in yield all over the world. Monitoring is done through laborious and error-prone traditional methods of scouting. The monitoring of diseases and pests is an effective cure that is offered by drones.

Disease Hotspot Detection: Drones can detect the local hotspots of disease outbreak by taking the image of the canopy color and abnormalities in texture.

Insect Population Monitoring: Drones are capable of identifying the patterns of damage caused by pests in crops e.g. defoliation or discoloration.

Early Intervention: Early detection using drones ensures the early application of pesticides or biological agents minimizing the possibility of wide-scale outbreak and reducing the chemical applications. This method not only protects the yields but also promotes agricultural activity that is not harmful to the environment.

Yield Estimation and Harvest Planning

Estimation of the yield is essential for the planning of farms, supply chain, and prediction of markets. Yield forecasting traditionally relied on sampling and manual observation and is imprecise and time-consuming. Drones make it a better process by providing precise and large data.

Biomass Estimation: Drones can estimate the accumulation of biomass by mapping the canopy density, plant height and chlorophyll content and thereby with potential yield.

Harvest Readiness: Crop maturity stages can be determined by using spectral reflectance derived from drones to help farmers make an informed decision about when best to harvest crops.

Spatial Yield Variability: Farmers can identify fields into high and low yielding areas from yield maps generated from drone photography.

This is improving not only the productivity of the harvest but also post-harvest logistics and supply chains management of markets.

Weed Detection and Management

Weeds are competing with the crops for water, nutrients, and light and effectively reducing the yields. High-resolution images are provided with drones allowing to detect weeds in the process of early.

Spectral Differentiation: Weeds tend to have dissimilar spectral signatures to crops and hence can be easily learnt to distinguish weeds using multispectral imagery.

Spatial Mapping: Drones are being used to create maps of weed distributions where targeted application of herbicide or mechanical weeding can be applied.

Cost Reduction: Precision weed control involves lower 40-60% of herbicides use, so it will reduce input cost and environmental contamination (Perez-Ortiz et al., 2016).

Large Field Management

Aside from single treatments, drones are also end-to-end field-level analysis for farmers to improve farm management as a whole.

Field Boundary Mapping Drones are precisely used for mapping field boundaries for land management and record-keeping.

Soil and Topography Mapping: Drones used by drone operators that have helped with soil erosion risk and designing effective drainage systems may now be made possible with the development of digital elevation models or DEM.

Geographic Information System (GIS) and Artificial Intelligence Integration The data from drones, Geographic Information Systems (GIS) and artificial intelligence (AI) can be combined to facilitate the predictive modeling and decision support in mass precision agriculture.

Drone-based Crop Monitoring Case Studies

Several real-world case studies illustrate the game-changing application of drones in crop monitoring:

Asian Rice Cultivation: Drones in Japanese and Chinese rice paddies have increased pest detection and nitrogen levels to high levels, leading their production levels to increase by 10–15% (Tsouros et al., 2019).

European Vineyards: Vine stress is monitored using the multispectral camera drones within vineyards in Italy and Spain to produce quality grapes and to minimize the amount of irrigation required.

African Maize Production: Drones have been piloted to crop monitoring in Kenya and Ghana to enhance the efficacy of fertilizer application and minimize the losses of Fall Armyworm attack.

The following examples mark scalability and versatility of agriculture drone monitoring in different situations.

Soil and Irrigation management Drones.

Introduction

Sustainable agriculture is centred on soil and irrigation management because it directly relates to crop productivity, water use efficiency, soil health. Conventional methods of monitoring the soil and water include manual sampling of the soil and water, laboratory analyses, and ground sensors, which are all accurate but time consuming, expensive and spatially constrained. These processes are being revolutionized by autonomous drones with advanced sensors, cameras, and machine learning algorithms that can provide real-time, high-resolution, and spatially extensive data (Li et al., 2020). The use of unmanned aerial vehicles (UAVs) in soil and irrigation management helps farmers to identify soil heterogeneity, improve irrigation scheduling, and reduce water wastage, hence helping to achieve the objectives of precision agriculture.

Soil Mapping and Characterization Soil mapping involves mapping the soil type of an area to develop a plan detailing the physical and chemical properties of the soil.

Through drones, soil mapping can be completed by taking pictures of the land at an elevated level with multispectral, hyperspectral, and thermal cameras. Such sensors are capable of detecting changes in the soil property including soil texture, soil organic content, compaction, and salinity levels. Indirect measurements of soil fertility through the visualization of crop vigor are provided by normalized difference vegetation index (NDVI) and soil-adjusted vegetation index (SAVI), which are derived by drone images, e.g. (Torres-Sánchez et al., 2018).

Machine learning methods also improve the soil mapping process through processing of the information obtained by drones, and creating predictive models of soil features. This can help farmers to apply variable rate fertilization, which cuts on the amount of inputs used without compromising on soil fertility. The difference between drone mapping and classical soil sampling includes a reduced amount of labor, increased spatial resolution, and increased frequency of large field monitoring.

Water Stress Detection and Irrigation Scheduling

Water scarcity and poor irrigation systems are still common worldwide agricultural issues. Drones are also helping with the control of irrigation through stressed plant water and irrigation scheduling. Crop water stress can be detected by the variation in canopy temperature which can be measured with thermal cameras installed on UAVs. Warming canopy temperatures will indicate a lack of water, whereas cooling will indicate water sufficiency (Zarco-Tejada et al., 2013).

In addition to this, multispectral sensors can also be used to check the vegetation water indices like the normalized difference water index (NDWI) striving to measure the degree of hydration of the plants besides soil moisture variants. One way farmers use these indices is to ensure that they can use water where it is required and not through blanket irrigation that would merely lead to wastage of resources.

Drones with thermal imaging have already demonstrated the ability to accurately determine the high-water stress micro-zones in dryland crops systems, fruit orchards, and vineyards. It can be used to support precision irrigation methods, like fertigation and drip irrigation, that have the highest water-use efficiency (Gago et al., 2015).

Integration with Ground-Based and IoT Systems

Drones with ground sensors and Internet of Things (IoT) technologies are added to improve the performance of soil and irrigation management by drones. As an example, soil moisture sensors can be used to provide point data with different depths, and drones can provide data with a high level of spatial scope. The mixture of the two sets of data will enable farmers to gain better understanding of soil-water behavior (Shamshiri et al., 2018).

Secondly, UAVs may be imposed as data collection platforms of a wireless sensor network. They are capable of collecting data as soil probes and sending the data to cloud platforms to be processed. By doing so, real-time irrigation optimization, predictive water demand modeling, and smart autonomous irrigation systems developed using the AI-based decision support tools can be realized.

Erosion and Salinity Monitoring

Besides water stress and soil fertility, drones play a key role in identifying soil erosion and salinity. Higher resolution images allow distinguishing erosion and sedimentation patterns as well as topographic changes.. It is highly valuable where there is high risk of desiccation and land degradation.

Similarly, hyperspectral imaging detects spectral signatures due to salinity and thus farmers can manage saline soils through leaching or selection of salt-tolerant crops (Allbed & Kumar, 2013). Monitoring such variables at an early phase reduces soil degradation and sustains long-term agricultural productivity.

Economic and Environmental Benefits

Soil and irrigation management with drones is several advantages. Economically, it is water and fertilizer cost-saving through precise input placement. Environmentally, it promotes rational use of water, reduces runoff, and limits groundwater contamination from over-irrigation.

For example, a study conducted by Padua et al. (2019), recorded how drone management of irrigation in Mediterranean vineyards, reduced the use of water by a maximum of 25%, without affecting or even improving the quality of the grapes. This shows that there is indeed an ability of UAVs to reach both productivity and conservation goals.

Limitations and Challenges

Though advantageous, drone-based management of soil and irrigation is subject to some restrictions. High resolution sensors are costly and analyzing the data needs high technical expertise. In certain areas cloud and weather conditions can restrict the use of aerial imagery. In addition, though drones enable surface-level information, they do not present complete substitution for deep subsurface soil analysis. Thus, UAV technologies need to supplement, not replace, traditional soil testing procedures.

Drones in Pest and Disease Management

Pests and plant diseases represent some of the most significant threats to agricultural productivity worldwide, responsible for up to 40% of crop losses annually (Food and Agriculture Organization [FAO], 2021). Traditional approaches to pest and disease management often involve manual field scouting, broad-spectrum pesticide application, and reactive treatment strategies. While these approaches can be effective, they are frequently labor-intensive, costly, and environmentally damaging.

Data Security and Privacy Issues

Drones have the potential to capture sensitive farm data such as crop health, soil fertility and yield estimates. Without effective data protection systems, the farmers are at risk of data abuse or misuse of their information by third parties such as agribusiness companies or government (Walter et al., 2020). Additionally, compliance-friendly cloud platforms that have security breaches as they endure security threats of the type that is placed on them, cloud platforms are exposed to data breaches. The availability of drone with advanced imaging tools, sensors and spraying capabilities have offered opportunities of early detection and targeted treatment as well as environmentally friendly treatment options for pests and diseases.

Early Detection of Pests and Diseases

One of the biggest forte of drones come in an intensive and high frequency monitoring of crops. Unmanned aerial vehicle (UAV) equipped with multispectral and hyperspectral camera can measure small variations in plant physiology, including chlorophyll fluorescence, leaf color, or canopy reflectance, which are most likely to be the earliest signs of disease stress (Garcia-Ruiz et al., 2013). These technologies enable hot spots where pest infestation or pathogens have started multiplying up until upright eyes would find it difficult to notice.

Detection accuracy also is increased through the use of machine learning algorithms in conjunction with photos taken by drones. As an example, convolutional neural networks (CNNs) can be trained to identify crop diseases through aerial vision with more than 90 percent accuracy in pilot studies (Kamilaris and Prenafeta-Boldu, 2018). Farmers can cover long distances at low costs and bridge the gap in time between disease outbreaks and intervention with a combination of drones and artificial intelligence.

Targeted and Precision Spraying

Other than detection, drones have been widely used as a platform to apply pesticides and biopesticides with precision. Conventional spraying techniques involving the employment of tractor-mounted spray booms, or aerial spraying with manned aircraft inevitably lead to overutilization of chemicals and unwarranted drift into adjacent ecosystems and human health. Instead, drones can be programmed to spray on a specific site and deliver pesticides precisely at the point where those infestations are detected (Zhang and Kovacs, 2012).

Variable-rate sprayers make use of variable-rate technology (VRT) to apply chemicals to crops in the most efficient manner. This saves 40% of the use of pesticides, saves money, and minimizes the adverse impact on the environment (Shamshiri et al., 2021). Farmers are also able to access spaces that can not be reached by ground machinery i.e. slopes of flood lands.

Incorporation with Integrated Pest Management (IPM)

Drones are a good match with Integrated Pest Management (IPM), where the priority is put on environmentally friendly and cost-efficient means of controlling pests. Drones deliver real-time information on the pest population movements to ensure that the farmer makes an informed choice on whether to treat them with chemical means or not and whether biological control in the form of predators or pheromone traps are more advantageous (Barrientos et al., 2020). In this respect, the dependence on chemical pesticides is reduced and agriculture is preserved.

An example is drone photography, which can be used to survey areas that have high pest density levels and allow farmers to apply biological control agents on those areas selectively. Drones also can drop useful insects including Trichogramma wasps the larvae forms inside pest eggs and provides a chemical-free pest control method (Khan et al., 2021).

Cost and Labor Efficiency

Drone-friendly pest and disease management reduces the amount of field scouting and chemical application labor required by a significant amount. Rather than using human scouts who would manually inspect the crops taking time and have error chances, drones can survey hundreds of acres within minutes. This maximizes the efficiency of farm operation especially where it is large-scale.

In addition to it, mechanized pesticide application with the help of drones will minimized the amount of chemicals agitating farmworkers, enhancing workplace safety. The availability and affordability of drone services offered by cooperatives or third parties will be beneficial to small farmers who have limited resources to acquire heavy machinery, especially.

Challenges and Limitations

While many advantages are offered by drones, they are also beset with a host of challenges. Some of these technical challenges are having limited flight times due to battery restrictions, chemical spraying payload capacity constraint, and difficulties in badly weathered areas (Tokekar et al., 2016). The high initial capital costs on the drones with top-class imaging equipment remain out of reach for many small-scale farmers across most regions.

There are also regulatory and safety concerns surrounding drone spraying of pesticides. Almost all countries have strict regulations to control aerial spraying, with additional special licenses or permits required. Further, the aspect of realizing uniform spray coverage and consistent drop size remains a technical hurdle in front of drone spraying platforms (Qiu et al., 2017).

Future Prospects

Drone applications in disease and pest control are anticipated to grow as a result of their integration with satellite imaging, big data analytics, and Internet of Things (IoT) platforms. Predictive methods combined with real-time aerial picture transmission can offer dynamic pest infestation forecasts. Autonomous swarming drones that manage hundreds of drones in a coordinated manner are under investigation to enhance scalability and efficiency for applications in pest control.

Besides, with the improvement of pesticide formulations to be used in drone spraying, e.g., nano-formulated pesticides and bio-agents, the effectiveness and sustainability of drone-assisted pest control will improve. This advancement in technology puts drones at the heart of one of the mandates of precision agriculture: how to maximize productivity at the expense of environmentally sustainable action.

Drones in Harvest Management and Yield Prediction

Harvest management and yield estimation play an important role in precision agriculture since they affect food availability, profitability of farmers and the global food security. Accurate estimation of yield allows farmers to plan harvesting activities, post-harvest storage as well as sale contracts. The classical methods of predicting yield, such as manual sampling in the field or statistical modelling, are time consuming and laborious and can also be highly inaccurate due to variations in soil properties, plant development, and weather conditions (Jin et al., 2021). The use of drones that have high-tech sensors in imaging and software-based analytics based on artificial intelligence (AI) have revolutionized these processes with scalable and real-time detection and prediction for harvesting gravinas through highly accurate solutions to yield prediction and harvest planning.

Drones in Yield Forecasting.

A key component of the yield forecasting is the usage of drones that possess the ability to take high resolution photographs of the crop fields at various stages of growth. By combining the remote sensing sources with the machine learning models, drones can measure the health of plants, their canopy cover, biomass growth and nutrient uptake (Nguyen et al., 2020). These are excellent indicators of what the future of the crop yields might do. Unlike the satellite-based prediction models, drones have better temporal and spatial resolutions and enable field-level predictions to enhance the decision making of farmers.

Indicatively, hyperspectral, multispectral cameras mounted on drones capture high-resolution vegetation index such as Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) related to crop yield and development (Hassan et al., 2019). Drones can recreate yield patterns more accurately than the traditional methods of analysis of these indices throughout the cropping season. Photogrammetry-based three-dimensional (3D) crop canopy modeling also improves biomass estimation, an important predictor of ultimate yield.

Combination of Predictive Analytics and AI

Predictive modeling as part of artificial intelligence stands out as one of the largest leaps to drone-based yield prediction. When a drone provides data to apply machine learning models, predictions of yields can be made with astounding precision by aggregating environmental factors (soil health, irrigations data, and weather conditions) (Wang et al., 2021). Such AI solutions allow farmers to predict the change in field-to-field yields and therefore respond to it, e.g., by spotting fertilizer or irrigation trials, in order to maximize output.

Moreover, predictive models assist agribusiness stake holders (e.g., policymakers and supply chain managers) to make smart decisions regarding prices, transport, and food distribution. This degree of predictability is efficient at the farm level as well as the food security and stability of the general market (Li et al., 2020).

Harvest Timing and Management Drones

The quality and profitability of crops also depends on when the crops are harvested. Early picking can result in less production and a late harvest can result in a lower quantity of nutritional value and result in further waste due to spoilage or pest attacks. Drones also have the capability to determine the most efficient harvesting opportunities since they can scan the signs of maturity of crops in real-time (canopy color, moisture, and the size of fruits) (Rud et al., 2018).

Hyperspectral cameras on drones monitoring vineyards are one of these applications because they can measure pigment and water content and when grape sugar and acid levels are optimally high, the vineyard owner can retrieve the grape (Matese & Di Gennaro, 2015). In the case of cereal crop such as wheat and rice, the drones are used to determine the level of grain filling such that farmers can harvest the grain when the yields and quality of the grains are at the best.**Resource and Logistics Optimization at Harvest**

Besides predicting yield, drones can facilitate the handling of the logistics of the harvest. Drone technology assists farmers to map the variability of crops within the agricultural area with the aim of strategically placing harvesting machinery to the appropriate position to achieve the maximum efficiency in terms of less fuel consumed, less labour and less equipment service (Shamshiri et al., 2018). Drones are also used to generate yield maps that can be used to plan better after harvest including how much storage will be needed, and how it can be transported.

Drones with Geographic Information Systems (GIS) enable farmers to employ more specific harvesting strategies in the agricultural system that is based on commerce. Their allocation of resources is dictated by the variability on geographical yields which is the most efficient and least wastage. This combination is especially useful in developing countries, a place where labor shortages and a higher cost of operations for harvests put pressure on food supply chains.

Drone-Based Yield Prediction Case Studies

Some studies show the successful use of drones for harvesting and yield studies. For instance, NDVI maps obtained from the drone were compared with manual estimates in rice growing, and successfully predicted the yield with high accuracy (more than 90%) (Yang et al., 2017). Drones equipped with RGB cameras were also able to give early-season predictions for Crops Like maize which improved harvest planning and farmers able to use nutrients optimally (Bendig et al., 2015).

Another example is in apple orchards, where drone technology is being used to count apples per tree using computer vision algorithms to estimate yields with high accuracy (Sa et al., 2016). These are few examples of how drones may bridge the gap between data-driven agriculture management and the traditional yield estimation techniques.

Limitations and Future Directions

In spite of such advantages, the widespread use of the drone-based method of yield prediction has its limitations. Large expenditures on specialized imaging devices, standardization of data and sensor calibration can make it difficult to provide access to small farmers (Wolfert et al., 2017). Weather patterns may also no be predictable, therefore reducing the accuracy of predicting.

The next step is to develop low cost sensors, open source forecasting models as well as integration with Internet of Things (IoT) platforms. This technology will enable real-time information exchange between supply chains to improve the predictability and effectiveness of yield and harvesting, throughout the rest of the world. Moreover, the advancements in AI are going to enhance forecast models by adding then the dynamic factors such as the effects of climate change, pests infestation and the market environment.

Challenges and Limitations of Drone Use in Agriculture

Despite the significant utility of drones in precision agriculture, the tool is not devoid of a number of challenges and limitations that limit the use of this technology, especially in low- and middle-income countries (LMICs). Although technology has increased the accessibility of drones, there are deep obstacles to cost, regulation, technical know-how, infrastructure, and environmental challenges. Such issues should be known to enhance the sustainable integration of drones into emerging agricultural systems.

High Expenses and Financial Thresholds

Drone technology as a start-up investment is still beyond the means of most farmers. Advanced agricultural drones with multispectral sensors, thermal imaging cameras or LiDAR sensors can range several thousand dollars, not to mention additional costs in the form of maintenance, batteries and software subscription (Rani et al., 2021). For small holder farmers, especially in developing countries, the ROI cannot be directly tangible and therefore it is unfavourable to adopt it. Though rental services and cooperative ownership structures have developed as alternatives, the cost issue still remains a limiting factor (Walter et al., 2020).

Technical Competence and Skill Deficits

Operating drones requires special technical competence, such as flight planning, data acquisition and geospatial imagery interpretation. Farmers will probably struggle to learn these skills especially in rural areas where training and agricultural extension services are not readily available (Colomina & Molina, 2014). Moreover, the interpretation of the data resulting from the use of drones (e.g. vegetation indices such as NDVI) is sometimes complicated and requires advanced data analysis and geographical information systems (GIS), which is not the strong point for the majority of farmers. This reliance on third parties would put a bad reputation on the cost-effectiveness of the adoption of drones.

Legal and Regulatory Restraints

Aviation laws and regulations have a large impact on drone operation in agriculture. Many countries have strict rules about the flight of drones, their license, airspace restrictions and data privacy (Giones & Brem, 2017). Diverse regulatory environments in various geographies also make cross border collaboration in research and application in drones even more complex. For instance, though in some countries drones are to be registered and flown by licenced pilots only, in others, night flights or flights beyond the visual line-of-sight (BVLOS) are banned, thus restricting agricultural uses (Shamshiri et al., 2018). As a result, such regulations play a part in slowing down adoption, and especially with smallholder farmers.

Infrastructure and Connectivity Restrictions

Precision farming with Drones To name a few, precision farming involves the use of cutting-edge digital infrastructures such as high-speed internet, GPS, and cloud computing. Rural agricultural regions also are poorly served with poor or no connectivity to process and transfer data in real time (Tsouros et al., 2019). For the most developing countries, charge station for drone batteries cause operating limitation, which decrease their efficiency in big farm agriculture.

Environmental and Weather Constraints

Drones are very dependent on weather. Wind speed, rain, moisture and temperature fluctuation can all include impacting factors for drone stability, duration of flight and clarity of images (Hassanalian & Abdelkefi, 2017). In monsoon or desert climates, there could be a few weather disruptions which could limit the hours of drones working. As battery life is limited-most commonly at 20-40 minutes, it means drones cannot, in one go-around, cover very large farms. These environmental conditions make drones less dependable than a satellite monitoring system.

Integration Issues with Other Technologies

While drones do have the power to collect enormous amounts of agricultural data, the real possibility lies in combining them with other complementary technologies such as artificial intelligence, IoT-based sensors in the soil, and analysis of the big data. Yet with these technologies comes the need for huge investment in digital ecosystems and interoperability standards, that are limited in most farming applications (Shamshiri et al., 2018). Without integration, it is likely that drones will be underused as isolated tools and not a part of a complete precision agriculture system.

Social Acceptance and Ethical Issues.

Social and cultural issues also become obstacles to the adoption of drones**.** In some of the agricultural communities located in rural areas, farmers may have distrust toward drone technology due to the fact that they may not be exposed to it much or misunderstand the function of drone technology. Fears about surveillance and lost control over decisions within the agricultural space can serve as a source of resistance (Clarke & Moses, 2014). Ethical issues are also raised regarding the extent to which drone technologies are serving primarily the big value farmers and therefore are increasing the inequality with the resource-poor smallholder agricultural producers who are not able to use these technologies.

Environmental Sustainability of Drone Production

Though they are sold as environmentally friendly machines that reduce the usage of chemicals and waste of resources, no one thinks of the process of creating drones as a sustainable one. Drone production uses rare earth metals, plastics, and lithium-ion batteries, which makes them a significant contributor in the e-waste and resource extraction effects (Tsouros et al., 2019). Unless a circular economy pathway is adopted to ensure a source of drones from the cradle to the grave, an environmental dividend from drones might be negated.

Future Prospects of Drones in Agriculture

The adoption of drones in agriculture is still in its formative stage, but with technological advancements coupled with increased demand for sustainable agriculture practices, it would seem that the use of drones in agriculture will become an increasingly important part of world food systems. Future opportunities for drones in agriculture are shaped by developments in artificial intelligence (AI), machine learning (ML), data analytics, and sensor technologies, which are likely to see results in precision, efficiency, and decision-making being achievable on agricultural landscapes. In addition the advance of regulations and falling costs will push the adoption at large scales throughout the developed and developing economies it is said.

The Artificial Intelligence and Big Data Integration.

Farm drones have an unbreakable connection with big data analytics and AI. Although the current systems using drones provide valuable insights on images and initial data, AI-powered drones will enable real-time and autonomous decision-making.Drones will combine the data of many sources such as weather predictions, soil status records, and the process by which the crops grow, and provide farmers with viable solutions. In the case of predictive analytics, one could predict the problem of pests or nutrient deficits before they accumulate into severe risks (Yang et al., 2020).

Advanced Sensor Technology.

Drones will become more competent due to miniaturization of sensors and hyperspectral, multispectral, and thermal imaging technologies. The next wave of sensors will recognize the crop stress on the molecular level and be able to intervene at the earliest possible, with precision unmatched by other approaches (Gevaert & Plaza, 2020). Future drones can also be equipped with gas sensors to track greenhouse gas emissions to maintain that the farms are geared towards climate-smart agriculture programs.

Autonomous Swarm Drones

One of the most radicals in the pipeline are swarms of drones. Instead of having a single drone performing a set of tasks, a swarm of drones can work as a team to cover vast areas of crops at a low cost. Such systems would be mostly independent and would reduce the amount of labor required. Swarming can be used in practice to illustrate this, such as by planting, spraying, and surveying the farm simultaneously (Shamshiri et al., 2021)..

Integration with Internet of Things (IoT) and Robotics

The drones will be more and more included in broader systems of smart farming, connected with IoT devices or autonomous working robots. Drones could be combined with autonomous tractors, automated irrigation systems and weather-monitoring stations to be the source of integrated precision agriculture. The information taken by drones would be transmitted to central farm management systems, which would provide farmers with a consolidated overview of activities (Wolfert et al., 2017).

Climate change mitigation and Sustainable Agriculture.

Future uses of drones will be significant in the climate resilient agriculture. Through the optimization of the use of inputs, drones have the ability to cut down on chemical runoff, greenhouse gas emissions and water loss. Additionally, drones can be used in support of reforestation activities, carbon sequestration activities and soil regeneration efforts, making them instrumental in the fight against climate change (Jat et al., 2021).

Economic Pre-eminence and Utilization in the Third World.

Despite the price factor that remains to be a hinder, the prospects are of inexpensive drone technologies. With the scaling up of production and competition, drones will be within reach of smallholder farmers especially in Asia and Africa. Governments and NGOs will promote drone-based solutions when developing agricultural development plans, adding to the rise in adoption (Tsouros et al., 2019).

Policy and Regulatory Developments

Agricultural use of the drone use is evolving at a rapid rate. It is expected that future policies will allow commercial utilization of drones, and there will be better policies on the use of airspace, security, and data protection. Easy policy will not only ensure that innovation is made easy, but also ensure that the use of drones becomes standardized with regard to ethical and safety (Clarke and Moses, 2014).

Drone-Based Supply Chain and Market Innovations

Other than at the farm level, drones would transform agricultural supply chains. Future drones will be capable of assisting with the transportation of the crops, the logistics of the market and the delivery of food even to the isolated locations. This can help minimize losses associated with after harvest and improve food delivery systems, which will increase food security (Radoglou-Grammatikis et al., 2020).

Education and Skill Development

As drones continue to be applied in agriculture, capacity-building and educating farmers also become potentially important in the future. The capacity-building and training programs as well as the extension services will play a significant role in empowering the farmers with skills to use, interpret and service the drone systems. Universities and agricultural schools will be requested to include drone technologies into the curriculum that will result in the generation of Agri-tech experts.

Long Term Vision: Fully Automated Farms.

The long-term vision for farm drones is that they would be part of completely automated agriculture systems. In this future scenario, drones will be employed as flying scouts, providing real time information to autonomous machines that will be seeding, irrigating, fertilizing, and harvesting crops. This vision is in line with the overall concept of Agriculture 5.0, where technology, sustainability and human guidance are combined to create very productive but environmentally clean food systems (Rose & Chilvers, 2018).

Ethical and Social Considerations

Although the perspectives are bright, even the ethics should be considered a consideration in the future. Such questions like who owns the data, privacy and access to the drone technologies equally will have to be addressed. Ensuring that the use of drones is advantageous to the small holder farmers, not necessarily the large-scale industrial farms, will be critical to the agricultural development at the level of the smallholder.

CONCLUSION

Precision agriculture involves the use of drones which is a paradigm shift in the modern agricultural practices which has combined technology with green agricultural practices. As this paper has revealed, drones are no longer experimental devices but useful commodities used in crop surveillance systems, soil and irrigation management, pest and disease surveillance, harvest optimization, and yield estimation. By providing real-time and high-resolution data, farmers can make informed decisions, which are based on data, and the result will be increased productivity, reduced resource costs, and sustainability of the environment.

The evolution of drones in agriculture through the years, starting with primitive aerial imaging systems, and rising to highly sophisticated sensor-enabled drones, is a betrayal of the versatility of drones and their growing use in solving new agricultural challenges. Using remote sensing concepts, geographic information systems (GIS), and artificial intelligence (AI), drones can transform the complicated agricultural systems into measurable, manageable entities amid a worldwide quest of intelligent and profitable food systems.

Economically, drones save money as it minimizes the wastage of inputs and has the capacity to maximize production, whereas socially, they enable farmers to have access to affordable technological solutions to improve their livelihoods. Precision farming with drones results in reduced reliance on a chemical-based approach to the environment and creates more sustainable land and climate resilience.

However, the obstacles to the implementation of the drones, including regulatory restrictions, technical issues, the excessive initial cost of using the drones, and the necessity of actual training of the specialists, point to the fact that the drone usage on large scale will have to be a combined government-industrial-scientific initiative.

The future of the drones in the agricultural industry is promising in the future. The efficiency, accuracy, and low cost of drones will only grow moving forward, as an ever-growing number of developments integrate into the field of artificial intelligence, machine learning, Internet of Things (IoT) connectivity, and automation. As the battery life, payload, and sensor technology continue to improve, the role of drones in addressing various problems of global concern, such as food security, climate change adaptation, and sustainable management of resources, will be even more prominent.

Altogether, drones in precision agriculture are not only a technology but an impetus of a new era of agriculture that would be sustainable, data-driven, and robust. Despite the challenges, the development and use of drone technologies will form the future of agriculture and agricultural systems will become efficient, sustainable, and capable of serving growing populations around the world.

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