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Integrating Drone Technology into Sustainable Agriculture for Improved Soil Health

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Soil health is of utmost importance when it comes to sustainable agriculture, as it influences crop productivity, plant nutritional quality, water consumption, and environmental stability. The classical ways of soil assessment are predominantly connected to the field sampling and laboratory testing which often involves great efforts and time resources, as well as poor spatial representativeness of the data. The sales of agricultural drones are expected to rise from $1.2 billion (USD) in 2019 to $4.8 billion (USD) in 2024 according to certain reports. The fast development of UAV technologies opens up new horizons regarding detailed and quick evaluation of agricultural sites. With the help of remote sensing by means of drones, the spatial information on vegetation state, soil moisture, soil surface variability, erosion, nutrient deficiency, and other factors related to soil health can be collected. The use of the technology allows for precise fertilization, irrigation, and spraying of pesticides, along with the unnecessary use of resources and any possible effect they may have on the environment. In this review, the applications, advantages, drawbacks, and future possibilities of the use of drones in the assessment of soil health and sustainable farming are considered. In particular, special emphasis is placed on the use of drone data in digital and precision farming.

Keywords: Drone technology, Soil health, Sustainable agriculture, Precision agriculture.

Drone in Agriculture

The primary goal of sustainable agriculture is to ensure that there will be no depletion of natural resources in order for future generations to utilize them effectively (Yadav *et al.*, 2026). The use of unmanned aerial vehicles, also known as UAVs, has become prevalent in the agricultural industry owing to its innovative way of controlling and tracking livestock and crops. Through the sensors and cameras attached to the aerial vehicles, farmers will be able to collect crucial information in making well-informed decisions that will result in sustainability, efficiency, and increased productivity. Apart from increasing the level of productivity, drones can help farmers to overcome various problems and get several advantages from precision farming. The agricultural drones market is projected to generate a revenue of $1.3 billion. UAVs meet the deficiency left by traditional farming practices' inefficiency and human errors. UAS were introduced for the use in agriculture by Japan with the introduction of spray chemicals in the 1980s and the crop dusting in the 1990s. In 2001, over 1,220 Yamaha unmanned helicopters had already been used and over 2,000 Yamaha RMAX helicopters have since then sprayed around 2.5 million acres per year and about 40% of Japan's rice fields (Nonami, 2002; Sato, 2003).

The purpose of drone technology implementation is to do away with any guesswork and ambiguity and replace them with accurate and dependable information. Various external factors such as climate, soil composition, and temperature are essential for farming. Soil poses various health risks in the form of diseases and can harm people through the food chain (Yadav *et al.*, 2026). Drones will be essential in enhancing efficiency in the application of crop protection chemicals in terms of reduction of manpower, time, amount of water, chemicals used and protection from exposure of human beings to hazardous substances (Kumar *et al.*, 2025). Drone farming allows the farmer to adapt to a certain environment and make informed decisions. As shown in figure 1 below, there is a marked growth in the market size for drones' technology around the world from $1.40 billion in 2021 to $7.90 billion in 2030 (Disaniya *et al.*, 2025).

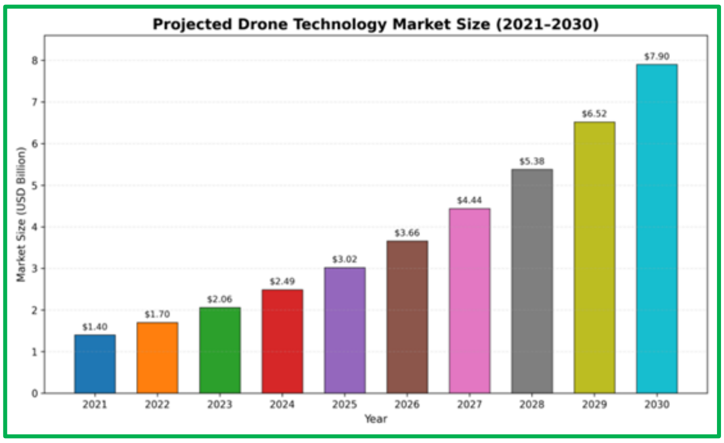

Fig. 1- Projected global market size of drone

The block diagram clearly shows figure 2 how a drone works in a systematic manner with four key components, namely: drone, sensors, control station, and communication system. The battery is responsible for supplying electricity to electronic speed controllers (ESC) that control the operation of motors and propellers in the flight process. The autopilot is the main controller of the drone and receives input from the sensors, namely GPS, compass, altimeter, and proximity sensors, while giving output to the motors and servos. Moreover, the drone contains a camera with shutter, tag, and roll functionalities for acquiring images. The modem onboard helps in communication with the control station. Radio receiver takes commands from the ground operator. In the control station, there are a laptop, modem, radio transmitter, and video receiver for monitoring flight status and getting images.

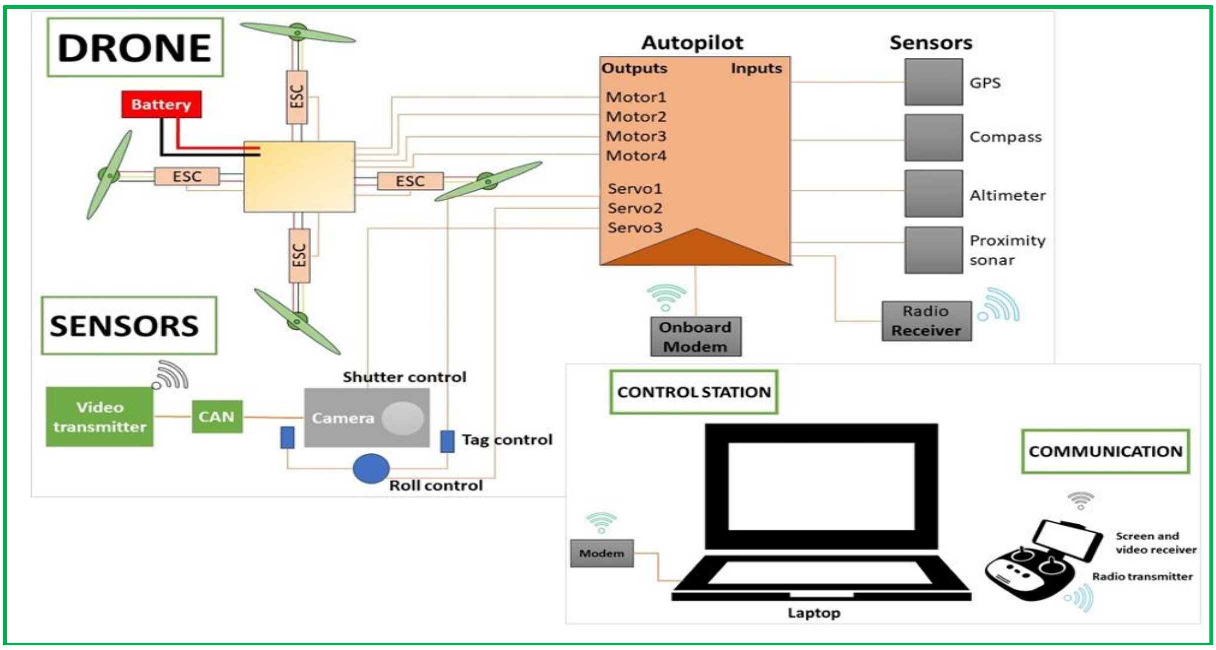

Fig. 2- Block Diagram of Drones System (Guebsi et al., 2024)

The Donut Chart figure 3 represents the level of awareness of the respondents. It represents that 73.3% are aware and are represented through the larger portion which is green in color, while 26.7% are not aware and represented through the smaller portion which is red in color. According to the data, it seems that almost three-quarters of respondents are aware of the matter under investigation, which means that there is quite a high level of knowledge or awareness in the case. But more than a quarter of respondents are not aware, which is a considerable portion of people who must be enlightened about the issue (Barathkumar et al., 2024).

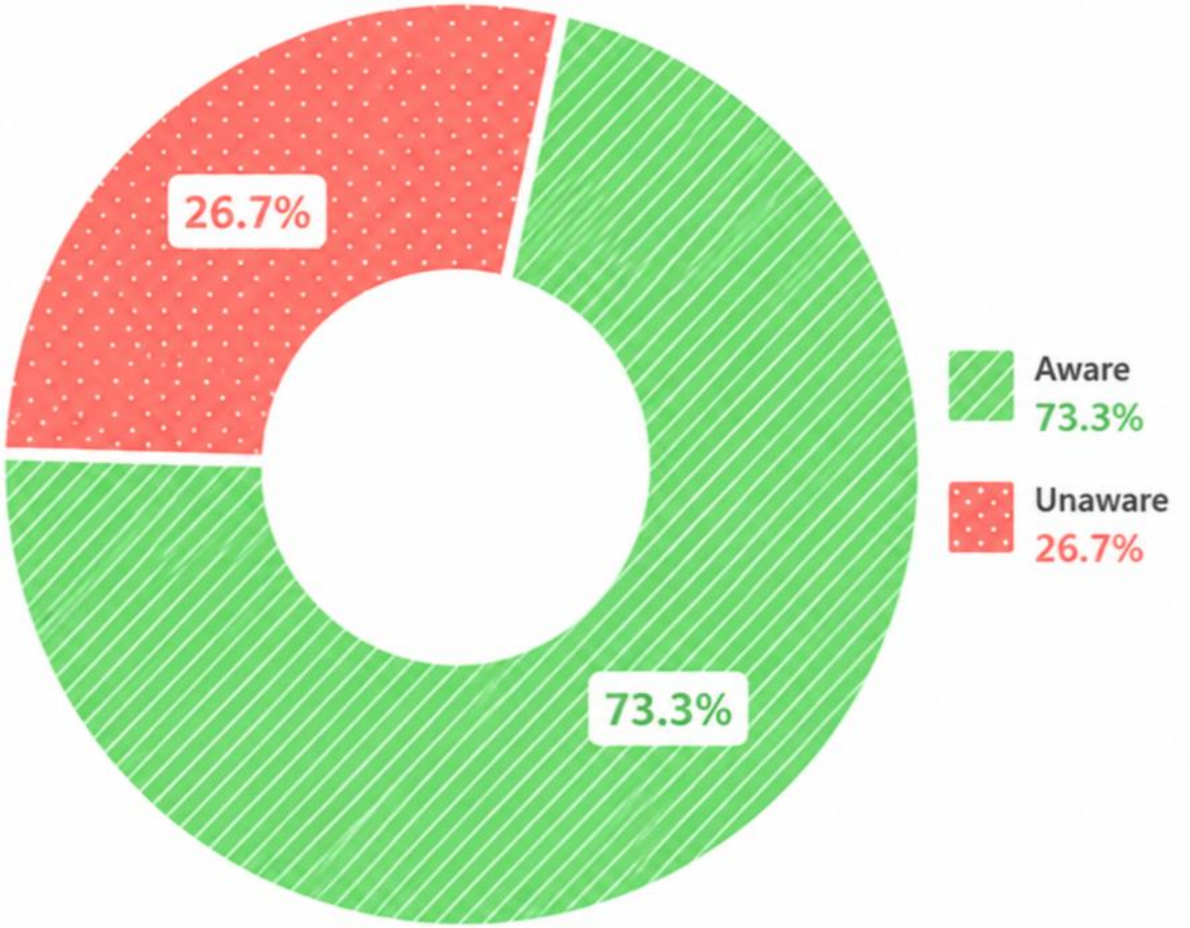

Fig. 3- Knowledge about drone technology

Drone Applications in Agriculture

Drones can have a variety of applications in agriculture, such as crop health monitoring and farm-related activities such as weed management, evapotranspiration estimation, spraying, etc. For agricultural purposes, regularized smart-farm solutions are being planned, such as the use of UAVs **(Singh *et al.*, 2024)**. The combination of technology of drones and swarm communication is quite an interesting solution for enhancing agricultural monitoring and productivity. The idea of dividing the agricultural fields into sectors and monitoring their condition using several drones will be helpful to detect the differences in fields and take appropriate actions on time. The application also reveals the possibility of manufacturing lightweight drones from recycled marine plastics. Thus, drones can save time for monitoring, become economically viable and promote sustainable development in agriculture. The following are some of the significant applications of drones in agriculture:

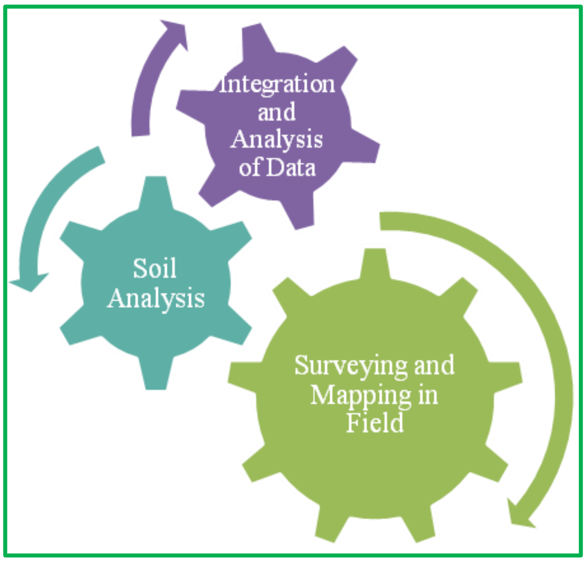

Fig. 3- Major Applications of Drone in Agriculture

The table 1 highlights the compatibility of different types of drones to various agricultural operations. The multi-rotor drones have been identified to have high suitability in the agricultural operations of soil-conditioning, planting, pest control, and crop surveillance. However, they have low suitability for agricultural spraying operations. The fixed-wing drones have medium suitability in soil assessment, planting, and spraying. They have high suitability in pest control operations, although their suitability in crop surveillance is relatively low. The single-rotor drones have high suitability in soil assessment, crop planting, and surveillance. Their suitability in pest and livestock assessment is relatively medium. The fixed-wing drones have high suitability in agricultural spraying and livestock assessment, although low in soil assessment, pest control, and crop surveillance.

Table 1- Comparison of Drones in Relation to Best Practices (Fafolawala et al., 2025)

Best Practices in Agriculture	Multi-Rotor	Fixed-Wing	Single-Rotor	Fixed Wing
Estimating soil condition	Good	Moderate	Good	Poor
Planting future crops	Good	Moderate	Good	Good
Fighting infections and pests	Good	Good	Moderate	Poor
Agricultural spraying	Bad	Moderate	Poor	Good
Crop surveillance	Good	Bad	Good	Poor
Livestock monitoring	Moderate	Moderate	Moderate	Good

Integration of drones in sustainable farming

Sustainable agriculture is one such system of agriculture, where production is done with regard to the natural resources or fulfilling the daily requirements of people without exploiting natural resources in order to achieve maximum production or natural resources for future generations (Kushwaha & Dayal, 2023). The main objectives of agriculture include fulfilling the requirements of humans without depleting natural resources, producing healthy and durable food and reducing soil and water pollution so that the future generations can effectively utilize the natural resources (Kushwaha & Dayal, 2023). Drones are revolutionizing sustainable farming through precise field observation, efficient resource use, and evidence-based decision-making. UAVs that use high resolution, multispectral, and hyper-spectral cameras can detect stresses, pest infestations, diseases, nutritional deficiencies, and water needs in crops at an early stage. This data helps with the accurate application of fertilizers, pesticides, and irrigation to minimize wastage of inputs and reduce costs and adverse impacts on the environment. Combining drones with AI, GIS, remote sensing, and precision agriculture would improve field observation even further. Although there are obstacles such as high costs, technical know-how, regulations, and data management, drone technology holds great promise for improving soil and crop health, conserving resources, and achieving sustainable agricultural development (Takhumova *et al.*, 2025). Key Dimensions of Integrating Drone Technology in Sustainable Agriculture listed below (Takhumova *et al.*, 2025);

- Improving Crop Health Surveillance
- Optimized Resource Management
- Environmental and Soil Protection
- Social and Economic Implications
- Regulatory and Ethical Approaches
- Integrating into Larger Digital Systems

Integrating Drone Technology to Improve Soil Health

Drone technology has been found to be very useful in fast and highly precise soil health assessment. Soil health assessment involves the use of certain soil properties to assess soil quality, productivity, and the sustainability of the land management practices (Kapat *et al.*, 2024). Soil health is defined as the ability of soil to function (Kapat *et al.*, 2024). Unmanned Aerial Vehicles (UAVs) fitted with multispectral and hyperspectral sensors are able to detect the differences in soil organic carbon, nitrogen, moisture, salinity and other soil properties.

Unlike the traditional method of soil sampling, the use of UAV for sensing enables farmers to obtain detailed information regarding the soil at a field level for specific soil management and precise nutrient application (Hossen *et al.*, 2021; Sevilla *et al.*, 2025). The use of UAV imagery together with GIS, remote sensing and machine-learning increases the accuracy in prediction and mapping of soil properties. UAV hyperspectral imagery can provide more precise information regarding soil organic carbon (Song & Zhang, 2026). Inclusion of drones in both field measurements and lab analysis can assist in improving soil health monitoring, efficient resource use, and sustainable agriculture. Drones facilitate fast assessment of moisture content, nutrients, organic carbon, soil salinity, and degradation for sustainable soil management.

- **Helps with nutrient management** – Pinpoints nutrient variability, allowing for site-specific application of fertilizers.
- **Soil moisture monitoring** – Enables detection of dry/wet areas and management of irrigation.
- **Soil organic carbon mapping** – Useful in monitoring SOC, which is a soil quality indicator.
- **Identifies soil degradation** – Detects erosion, salinity, compaction, and other forms of soil degradation.
- **Decreases input overuse** – Facilitates accurate fertilizer and water application, lowering environmental strain.
- **Enables continuous soil monitoring** – Allows for repetitive field observations.

Precision agriculture using the quasi-zenith satellite (QZS) system.

Precision agriculture drones fitted with cameras and sensors are flexible and can be used when the need arises. These drones allow one to scout and acquire necessary data that can be applied in precision agriculture (Kumar *et al.,* 2025). The procedure used in precision agriculture with the help of QZS system. Drones with multispectral cameras, LiDAR, GPS, and LEX receive data from the fields. This data is analyzed and integrated using GIS software. Data analyzed through GIS software can be applied in several agricultural applications such as crop health, soil and field analysis, plant growth, pests and weed control, weather reports, livestock management, geofencing, and field history.

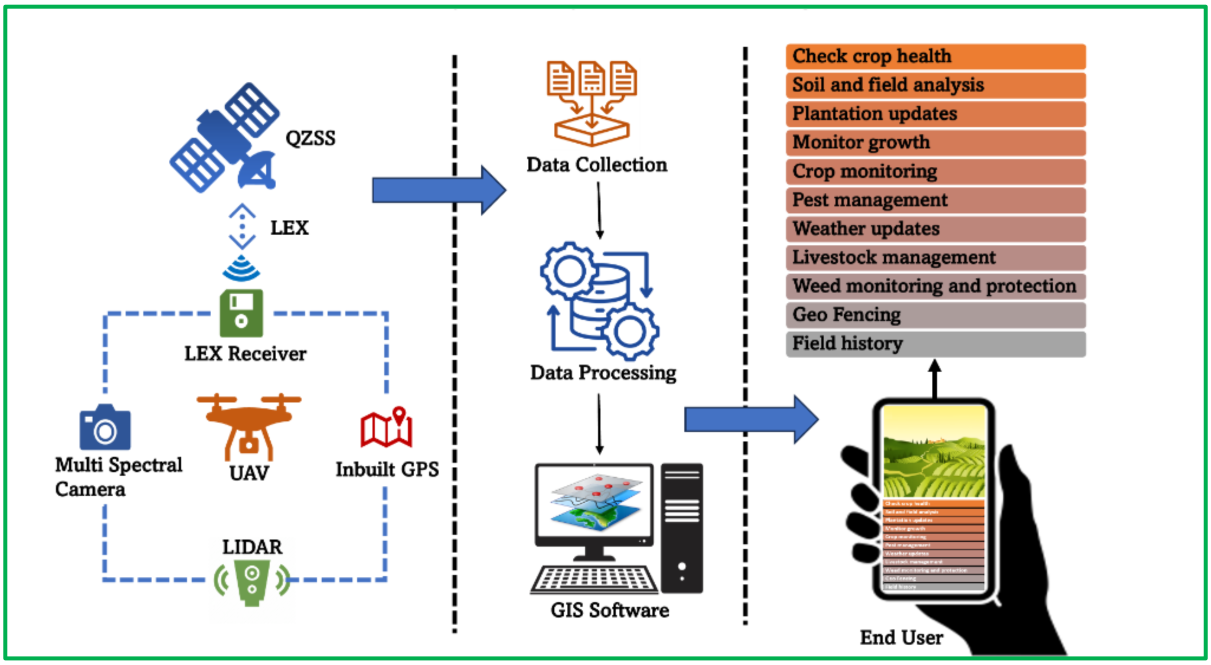

Fig. 3- Application of the Quasi-Zenith Satellite System in Precision Agriculture (Quamar *et al.*, 2023)

Conclusion

Drones represent a great chance to encourage healthy soils and sustainable practices in agriculture. High resolution of RGB, multispectral, hyperspectral, and thermal cameras makes the fast and non-invasive monitoring of soil moisture, nutrient stress, soil erosion, and other soil condition parameters possible. The data obtained through drone technology will help make precision fertilizing, irrigation, erosion protection, and efficient use of resources in agriculture possible. This will contribute to lower costs, waste, and negative environmental impact while boosting productivity. But there are several obstacles that need to be addressed, including high starting expenses, calibration, analysis, regulations, and validation of data. In the future, the combination of drones with artificial intelligence and machine learning technologies is expected.

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