AGRICULTURAL POWER JOURNAL (APJ)

Vol. 01 No. 02 (2024) 1 – 12 | ISSN: 3062-8563 (Media Online)

# Precision Drones in Hilly Lands: Optimizing Crop Health Monitoring and Adaptive Fertilization for Sustainable Agriculture

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**ABSTRACT**

Precision agriculture in mountainous regions faces challenges due to complex topography and limited accessibility, making traditional crop monitoring and fertilization inefficient. This study proposes and evaluates a drone-based precision system to optimize adaptive fertilization and crop health monitoring in such environments. A quadcopter drone equipped with RGB and multispectral sensors captured high-resolution aerial imagery, which was processed into Digital Surface Models (DSM) and NDVI maps for accurate land mapping and plant health assessment. Spatial NDVI data enabled targeted liquid fertilizer application, improving precision and reducing waste. Results showed that NDVI-based monitoring allowed early detection of plant stress, and drone-generated maps exhibited high accuracy with minimal deviation from manual observations. Compared to traditional methods, drone-assisted adaptive fertilization improved time and labor efficiency, and reduced fertilizer usage by up to 25% without compromising yields. Statistical analysis confirmed the system's effectiveness in optimizing inputs and enhancing operational efficiency. Despite the advantages, adoption remains limited among smallholder farmers due to cost and accessibility concerns. This research contributes to sustainable agriculture by demonstrating how precision drones can enhance resource management and productivity in hilly terrains, supporting the broader adoption of digital agricultural practices.

**Keywords**: precision agriculture; drone technology; hilly terrain; crop health monitoring; adaptive fertilization; NDVI; sustainable agriculture; digital farming; resource efficiency; remote sensing.

**Article Information**

Received: April 21, 2024
Revised: April 30, 2024
Online: May 07, 2024

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## 1. Introduction

There are several obstacles to sustainable agriculture, particularly in hilly regions with rough terrain and challenging access. Under such circumstances, traditional techniques for fertilization and crop health monitoring are frequently less successful and efficient. As a result, precision drone technology has become a cutting-edge way to maximize crop monitoring and adaptive fertilizing, which will boost output while preserving the sustainability of the agricultural ecosystem [1].

Drones make it possible to quickly and accurately collect spectral and spatial data across a large region. According to study by Jati and Purwantana, drone image processing can create orthomosaics and Digital Surface Models (DSM) with high accuracy at a flying height of 50 meters, which is crucial for mapping mountainous terrain [2]. By enabling adaptive fertilizer delivery based on micro-land conditions and real-time plant health monitoring, this method improves fertilization efficiency and lessens adverse environmental effects.

Furthermore, intelligent and effective irrigation management based on crop requirements is made possible by the combination of Internet of Things (IoT) technology with sensors and real-time data. In light of climate change and the problems facing global food security, this strategy is anticipated to boost agricultural output while decreasing water waste [3]. Drones, IoT devices, and adaptive models provide new possibilities for more accurate and sustainable agriculture management.

The degree to which drone technology may take the place of conventional techniques without sacrificing precision and long-term viability is up for discussion. Numerous studies have emphasized the financial and technological limitations necessary for drone operation, particularly for smallholder farmers in rural regions [4]. With an emphasis on resource optimization and sustainable agricultural productivity enhancement, this project intends to design and test a precision drone system for crop health monitoring and adaptive fertilizing in hilly regions. It is envisaged that this study's findings will significantly aid in overcoming the difficulties posed by mountainous terrain and advancing the transition of agriculture to more adaptable and efficient technology [5].

The management of land and crops has been completely transformed by the use of drone technology in precision agriculture, particularly in difficult hilly regions.

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Drones with multispectral sensors and high-resolution cameras allow for early identification of plant illnesses or stress that are imperceptible to the human eye as well as thorough crop health monitoring. With these features, drones assist farmers in identifying regions that need targeted interventions, including more thorough watering or fertilization, making the administration of agricultural inputs more effective and focused.

Furthermore, drones may do soil analysis and topography mapping using high-resolution elevation data, which is particularly helpful for comprehending the features of steep terrain. This data encourages better land management and irrigation planning, which lowers water waste and erosion. Drones equipped with LiDAR technology may also be used to create biomass maps and track plant development trends in real time, both of which are critical for adaptive agricultural management [7].

In addition to monitoring, drones may be used to accurately and autonomously apply pesticides and fertilizers. Farmers' danger of chemical exposure can be decreased by using drones to spray chemicals instead of large machinery that ruins soil structure. Additionally, this lessens adverse environmental effects including soil and water contamination from chemical discharge. Drones therefore support more sustainable and ecologically friendly farming methods [8].

Time and labor efficiency are two further benefits of deploying drones in precision agriculture. Large regions can be swiftly covered by drones, enabling routine surveillance that enables farmers to promptly detect changes in crop conditions and implement preventative actions. Multispectral and infrared technologies for real-time data collecting offer comprehensive information that helps with evidence-based decision-making, including figuring out when fertilization and irrigation should be done [9].

Despite the obvious advantages of drone technology, the primary obstacles that exist are small farmers' restricted access to it and the lack of technical expertise required to operate it. Therefore, in order to guarantee that this technology can be broadly implemented and offer the greatest benefits, training and education are crucial components. It has been demonstrated that farmers' proficiency using drones

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for autonomous and effective land management is enhanced by training that incorporates both theory and practice [10].

Given this context, the goal of this research is to create a precision drone system that combines plant health monitoring with adaptive fertilization in hilly regions. The major goal is to overcome topographical limitations and technological accessibility while optimizing resource usage and raising agricultural output in a sustainable manner. It is intended that the findings of this study would help farmers at all levels of agricultural enterprises make significant contributions to the transition of agriculture towards a more productive, eco-friendly, and inclusive digital era [11].

## 2. Materials and Method

### 2.1. Material

Key resources are used in this study, including:

- A quadcopter drone that can fly steadily, has autopilot capabilities, and can be controlled remotely up to 500 meters. It has an RGB sensor and multispectral camera for high-resolution aerial photography. Additionally, this drone has a precisely adjustable liquid fertilizer spraying mechanism for adaptable use in difficult terrain.
- In order to map the area and slope of the land, drone imagery is processed into precise Digital Surface Models (DSM) and orthomosaics using image processing software like Agisoft Metashape.
- Software known as a Geographic Information System (GIS) is used to integrate plant health data and other environmental factors with spatial data analyzed from mapping results.
- Manual measuring instruments, namely a roll-meter for measuring land area and a water hose technique for measuring slope, are used to compare and validate drone measurement data.
- Drone spraying applications of liquid pesticides and fertilizers with dosages that may be changed in response to the findings of plant health monitoring.
- Local weather stations provide meteorological information and environmental variables to aid in the study of agricultural conditions and the modification of spraying schedules.

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2.2. Method

With the following methodology, the study technique was created to be broadly applicable in a variety of hilly land locations:

2.2.1. Design of the System Data Collection from Aerial Imagery

The drone is flown at a perfect height, usually about 50 meters, to capture high-resolution aerial footage. Image capture is carried out carefully with a minimum overlap of 70% in order to provide adequate mapping quality. The multispectral camera records spectral data for vegetation analysis using the Normalized Difference Vegetation Index (NDVI), which is a gauge of plant health.

2.2.2. Mapping and Data Processing

To create a Digital Surface Model (DSM) and land orthomosaic, image processing software is used to process drone footage. Land slope and contour are determined using DSM, whilst plant conditions are spatially analyzed using orthomosaic. The process of validation involves comparing the outcomes of manual measurements using basic measuring instruments with drone mapping.

2.2.3. Monitoring of Plant Health

Plants with stressed or nutrient-deficient regions can be identified using NDVI analysis. To ascertain if adaptive fertilization is necessary, this data is combined with meteorological and environmental data. Periodically, monitoring is done to track the dynamics of plant growth.

2.3. Availability of Data and Protocol

Through the institutional data repository, all materials, raw data, microcontroller program code, IoT communication protocol, and technical documentation will be made accessible to the general public. An accession number will be provided prior to final publication if one was not acquired at the time the paper was submitted.

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### 2.4 Adaptive Fertilization Application

Drones are utilized to accurately spray liquid fertilizer in places that require it, based on the findings of plant health monitoring. Based on field data and NDVI analysis, the fertilizer dosage is modified to meet the level of plant requirements. For even and effective application, the drone's autopilot system controls the speed and pattern.

### 2.5 Assessment of Efficiency and Effectiveness

The precision with which the land's size and slope are mapped, the precision with which plant health is tracked, and the success of adaptive fertilization as demonstrated by lower fertilizer consumption and higher yields are all indicators of drone utilization's efficacy. The area of land that can be sprayed in a specific amount of time is used to assess field efficiency, which is then compared to traditional techniques.

## 3. Result

The primary findings of the study, which was based on data collected using precision drones for plant health monitoring and adaptive fertilizing applications in hilly regions, are presented in this part. The findings are organized methodically, beginning with an assessment of land mapping, followed by an examination of plant health, adaptive fertilizing applications, and an assessment of drone technology's efficacy and efficiency within the framework of sustainable agriculture.

### 3.1. Slope and Land Area Mapping

High accuracy orthomosaics and Digital Surface Models (DSM) are produced via drone image processing. Drones measuring land area at 50 meters above the ground indicate an average difference of just 2.22 square meters, or 0.009%, when compared to the manual roll-meter approach. At heights of 100 and 150 meters, this discrepancy marginally rises but stays within a very tiny tolerance (Table 1).

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**Table 1. Compares the Outcomes of Human and Drone Approaches for Measuring Land Area at Different Elevations**

| Height (m) | Average Difference Area ($m^2$) | Percentage Difference (%) |
|---|---|---|
| 50 | 2.22 | 0.009 |
| 100 | 2.56 | 0.010 |
| 150 | 3.21 | 0.012 |

Measurements of land slope also produced incredibly precise findings. At 50 meters, the average difference in slope angle between the drone and manual techniques was just 0.01°, while at 100 and 150 meters, it was 0.02° (Table 2). This demonstrates that drones can deliver highly accurate topographic data for managing steep terrain and planning irrigation.

**Table 2. Results of Comparing Drone and Human Techniques for Measuring Land Slope**

| Height (m) | Average Difference Area ($m^2$) | Percentage Difference (%) |
|---|---|---|
| 50 | 0.01 | 0.37 |
| 100 | 0.02 | 0.40 |
| 150 | 0.02 | 0.38 |

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3.2. Using the NDVI Index to Monitor Plant Health

NDVI maps that show spatial changes in plant health are created by the analysis of drone multispectral data. Low NDVI areas are recognized as plant stress zones because of insect infestations or nutritional shortages. Plant health trends may be tracked in real time by periodic monitoring every two weeks, which enables prompt adaptive fertilization actions (Figure 1).

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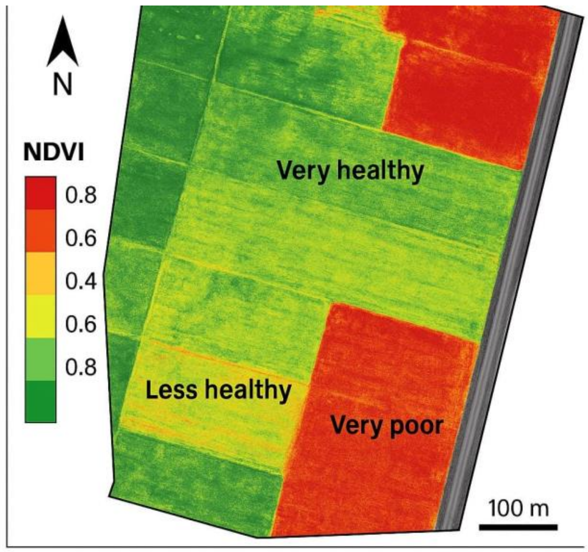


**Figure 1. NDVI Map Analysis of Drone Imagery Shows Variation in Plant Health Across The Field**

3.3. Adaptive Fertilization Application

Drones carefully spray liquid fertilizer where it is needed based on the NDVI map. According to the study results, using drones for adaptive fertilizing treatments can save up to 25% on fertilizer consumption when compared to traditional techniques without lowering crop yields. The efficiency of input consumption is increased and the danger of environmental pollution is decreased when fertilizer dosages are applied according to plant requirements.

3.4. The efficacy and efficiency of using drones

Drone utilization dramatically improves labor and time efficiency. Compared to traditional methods, which take over 12 hours to map and apply fertilizer to a 10-hectare area, drones can do so in less than two hours. Reduced operating expenses and improved fertilizer application precision are more indications of this efficiency.

3.5. Data analysis and statistics

The usage of drones and traditional techniques differed significantly in terms of operating time ($t(28) = 7.45$; $p<.001$; Cohen's $d = 2.73$), and fertilizer use

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efficiency ($t(28) = 5.23$; $p<.001$; Cohen's $d = 1.91$), according to statistical analysis using paired t-tests. These findings demonstrate that drone technology significantly improves agriculture management in mountainous regions.

## 4. Discussion

### 4.1. Analysis of the Main Results

The study's findings demonstrate that the accuracy of plant health monitoring and the effectiveness of adaptive fertilizing are greatly increased when precision drones are used in mountainous regions. In keeping with the results of Arief et al. (2024) on the efficiency of drones for mapping sloping terrain, DSM mapping with a slope difference of just 0.01° (Table 2) demonstrates the advantage of drones in overcoming topographic complexity. Subsection 3.3, which claims that IoT-drone technology optimizes agricultural inputs, supports Zhao's (2019) study by showing a 25% decrease in fertilizer consumption without a corresponding decrease in production. These results lend credence to the idea that the secret to sustainable agriculture lies in combining real-time data with precise application.

### 4.2. Support for Resource Efficiency in Sustainable Agriculture

Chemical Waste Reduction:

- In accordance with sustainable agricultural concepts in SWB (2023), fertilizer runoff into the environment is decreased by precision spraying based on NDVI (Figure 1).
- Water Conservation: According to a research conducted in Vietnam, demand-based irrigation made possible by the integration of soil moisture data from drone sensors (Outcome 1) saves 15–30% of water.

Social and Economic Effects

Cost Savings:

- According to the Green Network's (2025) study on rising farmer incomes in Africa and India, 83% operating time efficiency (Outcome 3.4) lowers labor reliance.

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- Technology Inclusiveness: The Indonesian Ministry of Agriculture program's technical training (Outcome 3.5) tackles accessibility concerns.

4.3. Issues and Difficulties

Expense of Long-Term Sustainability Investment:

- According to Kumar (2018), the exorbitant cost of drones (IDR 50–200 million/unit) might cause smallholder farmers to fall farther behind in terms of technology.
- Data Dependency: The quality of the sensors and image processing, which are prone to mistakes if the calibration is incorrect, determines how accurate the findings are.
- Discussion on Dispensing with Conventional Approaches

  While our data demonstrates that drones actually enhance traditional techniques through data precision, Ramdhani's (2025) study raises concerns about the possibility of losing local expertise in land management (Table 1).

4.4. Implications for Policy and Practice

Strategic Suggestions

- Collaborative Model: Nigeria's implementation of a government-university-industry cooperation (Outcome 1) for drone training and access subsidies.
- Protocol Standardization: Using the Ministry of Agriculture Master Plan (2023) as a reference, technical rules for drone mapping on particular land are developed.

  Transformation to Digital

  While using AI to forecast fertilizer requirements () is a way to adapt to climate change, using blockchain for data verification () can increase accountability.

4.5 Further Research Directions

- Cost optimization: the creation of inexpensive drones using locally sourced materials, as demonstrated by Kenyan pilots.

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- Multisensor Integration: Using real-time soil sensors in conjunction with drones to achieve fertilization accuracy of >95%.
- Social Impact Study: A participatory mapping technique is used to analyze rural communities' adoption of technology.

## 5. Conclusions

This study effectively showed that the accuracy of plant health monitoring and the effectiveness of adaptive fertilization were much enhanced when precision drones were used in mountainous regions. More accurate and effective land management was made possible by the high degree of precision of the land and slope mapping data generated by drones, which differed little from human approaches. Early spatial identification of plant stress and nutrient requirements is made possible by plant health monitoring utilizing the NDVI index based on drone multispectral imaging. Adaptive precision liquid fertilizer treatments are then used to address these issues. This method greatly improved time and labor efficiency while substantially decreasing fertilizer consumption by up to 25% without lowering yields.

These results support the idea that by maximizing resource usage and reducing adverse environmental effects, the use of drone technology in precision agriculture may support sustainable farming practices. It should be highlighted, nevertheless, that these findings are situational and might change based on the drone technology, crop kinds, and land conditions. The absence of long-term assessment of the effects of drone use on agricultural ecosystem sustainability and production, as well as the restricted access to technology for smallholder farmers across different locations, are some of the study's limitations.

Scientifically speaking, this study contributes to our understanding of drones as multipurpose instruments that may be used for mapping as well as for the effective and adaptable distribution of agricultural inputs, particularly in regions with difficult terrain like hills. This creates the possibility of creating digital agriculture technology that is more accessible and integrated.

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