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## Drone-Based Remote Sensing for Crop Health Monitoring in Tropical Agriculture

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### Abstract

Crop health monitoring is a critical component of agricultural productivity in tropical regions, where high rainfall variability, pest pressure, and rapid crop growth cycles complicate field-based assessment. Traditional crop monitoring methods, including manual scouting and satellite-based observation, often face limitations related to cost, spatial resolution, cloud cover, and timeliness. In response to these challenges, drone-based remote sensing has emerged as a complementary approach for capturing high-resolution, field-level data suitable for crop health assessment. This paper presents a structured synthesis of existing research on drone-based remote sensing for crop health monitoring in tropical agriculture. The review examines how unmanned aerial vehicles have been used to assess crop vigor, stress, and disease through multispectral, thermal, and RGB imaging. Particular attention is given to the types of sensors employed, vegetation indices applied, and analytical methods used to interpret crop health indicators under tropical conditions. The reviewed studies indicate that drone-based remote sensing can support early detection of crop stress, spatial variability analysis, and targeted field management when implemented under appropriate operational conditions. However, adoption in tropical agriculture remains constrained by regulatory barriers, operational costs, data processing complexity, and environmental factors such as cloud cover and high humidity. By synthesizing existing evidence through a tropical-specific lens, this review clarifies the practical conditions under which drone-based remote sensing can support crop health monitoring beyond experimental settings. The paper identifies key limitations in existing studies and highlights research gaps related to scalability, validation under farmer-managed conditions, and integration with routine farm decision-making in tropical systems.

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### 1. Introduction

Agriculture remains a central component of livelihoods, food security, and economic activity in tropical regions, where crop production is shaped by high rainfall variability, pest pressure, and rapid vegetation growth. In these environments, timely and accurate assessment of crop health is essential for managing yield risks, reducing losses, and supporting informed farm management decisions. However, traditional field-based crop monitoring methods rely heavily on manual scouting, which is labor-intensive, time-consuming, and often limited in spatial coverage (Zhang and Kovacs, 2012).

Remote sensing has long been used to support crop monitoring by providing spatially explicit information on vegetation condition. Satellite-based remote sensing systems have enabled

large-scale assessment of crop vigor, stress, and productivity through vegetation indices and spectral analysis (Mulla, 2013). Despite their value, satellite platforms face limitations in tropical agriculture. Frequent cloud cover, coarse spatial resolution, and fixed revisit intervals restrict their usefulness for field-level decision-making, particularly for small and heterogeneous farms common in tropical regions (Thenkabail et al., 2012; Justice et al., 2013).

In response to these limitations, unmanned aerial vehicles, commonly referred to as drones, have emerged as a complementary remote sensing platform for agricultural monitoring. Drones can capture high-resolution imagery at flexible times and under user-defined flight conditions, allowing detailed observation of crop variability within and across fields (Zhang and Kovacs, 2012). Equipped with RGB, multispectral, or thermal sensors, drone systems enable the detection of crop stress indicators related to nutrient deficiency, water stress, pest damage, and disease onset (Hunt et al., 2010).

A growing body of research demonstrates the application of drone-based remote sensing for crop health monitoring across a range of crops and production systems. Studies have shown that vegetation indices derived from drone imagery, such as the Normalized Difference Vegetation Index, can provide reliable indicators of crop vigor and biomass at fine spatial scales (Bendig et al., 2014). In tropical environments, where crop growth can change rapidly, the ability to conduct frequent and targeted data collection offers clear advantages over satellite-based approaches.

Despite these advantages, the adoption of drone-based remote sensing in tropical agriculture faces practical constraints. Operational challenges include limited technical capacity, regulatory restrictions on drone use, data processing complexity, and the cost of equipment and software (Tsouros et al., 2019). Environmental factors such as high humidity, variable lighting conditions, and dense vegetation can also affect image quality and data interpretation in tropical settings (Atzberger, 2013).

Moreover, many drone-based crop monitoring studies are conducted under experimental or research-managed conditions, with limited validation under farmer-managed systems. This raises questions about the transferability of reported results to real-world agricultural contexts, particularly for smallholder-dominated tropical farming systems. There is also variation in sensor selection, flight parameters, and analytical methods across studies, which complicates comparison and synthesis of findings (Mulla, 2013).

Given these considerations, a structured synthesis of existing research is needed to clarify how drone-based remote sensing has been applied to crop health monitoring in tropical agriculture, what benefits have been demonstrated, and what limitations remain. Such analysis is necessary to move beyond technical demonstrations toward a realistic understanding of the role drones can play in supporting agricultural monitoring and management in tropical environments.

This paper addresses this need by presenting a structured review of peer-reviewed studies that examine drone-based remote sensing for crop health monitoring in tropical agriculture. The review focuses on sensor types, analytical approaches, and reported applications, while also considering operational and environmental constraints. By synthesizing existing evidence, the paper aims to clarify the practical potential and limitations of drone-based remote sensing for crop health assessment in tropical agricultural systems.

## 2. Literature review

This section reviews existing literature on drone-based remote sensing for crop health monitoring, with emphasis on applications relevant to tropical agricultural systems. The review synthesizes findings from peer-reviewed journals and conference papers, examining how unmanned aerial vehicles have been used to assess crop condition, detect stress, and support agricultural monitoring. Attention is given to sensor technologies, analytical approaches, and operational considerations that shape the effectiveness of drone-based monitoring in tropical environments.

### 2.1 Crop Health Monitoring in Tropical Agriculture

Crop health monitoring refers to the systematic observation and assessment of crop condition to identify stress, disease, and variability that may affect yield and quality. In tropical agriculture, effective crop health monitoring is particularly important due to rapid crop growth, high rainfall variability, and persistent pressure from pests and diseases (FAO, 2011). These factors can cause crop stress to develop quickly, making delayed detection costly for farmers and agricultural managers (Mulla, 2013).

Traditional crop health monitoring in tropical regions relies largely on visual field inspection and periodic agronomic surveys. Farmers and extension agents assess plant color, growth patterns, and visible damage to infer crop condition. While these methods provide direct field-level insight, they are labor-intensive and limited in spatial coverage. Large or fragmented fields are difficult to monitor consistently, and subtle stress symptoms may go unnoticed until yield losses become evident (Atzberger, 2013).

Environmental conditions in tropical regions further complicate crop monitoring. Frequent cloud cover and high humidity affect both field access and the use of satellite-based monitoring systems (Thenkabail et al., 2012; Justice et al., 2013). Crops often exhibit high spatial variability due to differences in soil moisture, nutrient availability, and microclimatic conditions within short distances. As a result, crop health assessments based on limited sampling points may fail to capture within-field variability that influences management decisions (Mulla, 2013).

Crop health indicators commonly used in tropical agriculture include leaf area development, canopy color, plant height, and biomass accumulation. These indicators are closely linked to physiological processes such as photosynthesis and water use efficiency. Changes in these indicators can signal nutrient deficiency, water stress, pest infestation, or disease presence. Early identification of such changes is essential for timely intervention, particularly in systems where crop cycles are short and input use must be carefully managed (Zhang & Kovacs, 2012).

The literature emphasizes that effective crop health monitoring should provide timely, spatially explicit information that supports site-specific management. In tropical agriculture, this requirement is challenging to meet using conventional methods alone. Variability in farm size, cropping patterns, and management practices increases the demand for flexible monitoring approaches that can adapt to diverse production conditions (Atzberger, 2013).

As a result, researchers have increasingly explored remote sensing approaches to complement traditional crop monitoring practices. These approaches aim to improve the frequency, consistency, and spatial detail of crop health assessments. Understanding the limitations of

conventional monitoring methods provides important context for evaluating the role of drone-based remote sensing in tropical agricultural systems, which is examined in subsequent sections.

## **2.2 Conventional Crop Monitoring Approaches and Their Limitations**

Conventional crop monitoring approaches in tropical agriculture rely on a combination of field-based observations, agronomic surveys, and satellite remote sensing. These methods have supported crop assessment for decades and remain widely used due to their familiarity and relatively low technical requirements. However, their effectiveness in tropical environments is constrained by operational, environmental, and scale-related limitations (Becker-Reshef et al., 2010).

Field-based monitoring is the most common approach used by farmers and extension services. It involves visual inspection of crops to assess plant vigor, color, pest damage, and disease symptoms. While direct observation allows for contextual interpretation, it is time-consuming and depends heavily on the experience of the observer. In tropical systems where crop growth is rapid and stress conditions can develop within short periods, infrequent field visits may fail to detect early signs of crop deterioration (Atzberger, 2013).

The spatial coverage of field-based monitoring is also limited. Large farms, fragmented plots, and difficult terrain reduce the feasibility of systematic field inspection. As a result, assessments are often based on a small number of sampling points that may not represent overall field conditions. This limitation is particularly significant in tropical agriculture, where within-field variability in soil moisture, nutrient availability, and microclimate is common (Mulla, 2013).

Satellite-based remote sensing has been widely adopted to address some of these challenges by providing repeated, large-scale observations of crop conditions. Satellite imagery enables the use of vegetation indices to monitor crop vigor and seasonal trends. However, in tropical regions, persistent cloud cover significantly reduces data availability and limits the temporal resolution of usable imagery (Atzberger, 2013). Coarse spatial resolution in many satellite products further restricts their usefulness for smallholder-dominated landscapes, where fields are small and heterogeneous.

Another limitation of conventional monitoring approaches is the delay between data acquisition and decision-making. Field surveys require manual data collection and reporting, while satellite data often involve processing delays. These time lags reduce the ability of farmers and managers to respond promptly to emerging crop stress, particularly during critical growth stages (Mulla, 2013).

Cost and accessibility also influence the effectiveness of conventional crop monitoring. Regular field surveys require labor and transportation, while high-resolution satellite imagery may be costly or unavailable for routine use. In tropical agriculture, where resource constraints are common, these factors limit the frequency and scale of monitoring activities (Zhang & Kovacs, 2012).

Overall, conventional crop monitoring approaches provide valuable information but are often insufficient to meet the demands of timely, field-level crop health assessment in tropical

environments. Their limitations in spatial resolution, temporal frequency, and operational flexibility have motivated the exploration of alternative monitoring tools.

### **2.3 Drone-Based Remote Sensing for Crop Health Assessment**

Drone-based remote sensing has gained attention as a flexible tool for assessing crop health at fine spatial and temporal scales. Unlike satellite platforms, drones can be deployed on demand and flown at low altitudes, allowing the capture of high-resolution imagery tailored to specific fields and growth stages (Colomina and Molina, 2014). This capability is particularly relevant for tropical agriculture, where rapid crop development and frequent cloud cover limit the usefulness of satellite observations (Zhang and Kovacs, 2012).

Drones used in agricultural monitoring are commonly equipped with RGB, multispectral, or thermal sensors. RGB cameras provide detailed visual information that supports assessment of canopy structure, plant density, and visible stress symptoms (Lelong et al., 2008). Multispectral sensors capture reflectance in specific wavelength bands, including near-infrared, which enables calculation of vegetation indices linked to crop vigor and photosynthetic activity (Zarco-Tejada et al., 2013). Thermal sensors are used to infer plant water status by detecting canopy temperature variations associated with transpiration (Hunt et al., 2010; Mulla, 2013).

Vegetation indices derived from drone imagery are widely used to assess crop health. The Normalized Difference Vegetation Index is among the most commonly applied indices, serving as an indicator of green biomass and canopy vigor. Studies have shown that high-resolution NDVI maps generated from drone data can reveal within-field variability that is not detectable through conventional monitoring approaches (Bendig et al., 2014). In tropical cropping systems, where nutrient and moisture conditions can vary over short distances, such spatial detail is valuable for targeted management.

Research has demonstrated the application of drone-based remote sensing across a range of crops, including cereals, legumes, and horticultural crops. Drone imagery has been used to identify areas affected by nutrient deficiency, water stress, pest damage, and disease (Berni et al., 2009). These applications are often validated against ground measurements such as biomass, leaf area, or yield, showing moderate to strong correlations under controlled conditions (Bendig et al., 2014; Zhang and Kovacs, 2012).

Despite these promising applications, the effectiveness of drone-based crop health assessment depends on appropriate flight planning, sensor calibration, and data processing. Factors such as flight altitude, image overlap, and illumination conditions influence data quality. In tropical environments, variable lighting and atmospheric conditions can affect reflectance measurements, requiring careful preprocessing to ensure reliable results (Atzberger, 2013).

### **2.4 Environmental, Operational, and Institutional Constraints in Tropical Agriculture**

The application of drone-based remote sensing in tropical agriculture is shaped by a set of environmental, operational, and institutional constraints that influence data quality, feasibility, and adoption. These constraints are particularly relevant in tropical regions, where climatic conditions, farm structure, and regulatory environments differ from those in temperate agricultural systems (Wallace et al., 2012).

Environmental conditions in tropical regions pose significant challenges for drone-based data collection. High humidity, frequent rainfall, and variable cloud cover affect flight scheduling

and image quality. Rapid changes in illumination due to cloud movement can introduce inconsistencies in reflectance values, which complicates the interpretation of multispectral data and the calculation of vegetation indices (Atzberger, 2013). Dense crop canopies and overlapping vegetation structures common in tropical systems can also limit the ability of optical sensors to capture understory conditions accurately.

Operational constraints further affect the deployment of drones for crop health monitoring. Drone flights require careful planning, including selection of appropriate flight altitude, overlap, and timing relative to crop growth stages (Finn and Wright, 2012). In tropical agriculture, short crop cycles and rapid phenological changes increase the need for frequent data collection, which can raise operational costs and labor requirements (Zhang and Kovacs, 2012). Battery limitations and sensitivity of electronic components to heat and moisture also restrict flight duration and reliability under tropical field conditions.

Data processing and analysis represent another operational challenge. Drone-based remote sensing generates large volumes of high-resolution imagery that require specialized software and computational resources for processing. Tasks such as image stitching, radiometric correction, and vegetation index calculation demand technical expertise that may not be readily available to farmers or extension services in tropical regions (Mulla, 2013). These requirements can limit the practical use of drone data for routine crop monitoring.

Institutional and regulatory factors also influence drone adoption in agriculture. Many countries have introduced regulations governing drone operation, including restrictions on flight altitude, airspace access, and operator certification. While such regulations aim to ensure safety and privacy, they can create barriers to agricultural drone use, particularly where approval processes are complex or poorly defined (Tsouros et al., 2019). In tropical regions with limited regulatory clarity, uncertainty around legal compliance may discourage investment in drone technology.

Economic considerations intersect with these institutional constraints. The cost of acquiring drones, sensors, and processing software can be prohibitive for small-scale farmers, who dominate agricultural production in many tropical regions. Without clear evidence of economic return, adoption remains limited to research projects or well-resourced commercial operations (Zhang & Kovacs, 2012). Access to training and technical support further shapes the ability of stakeholders to integrate drone-based monitoring into routine agricultural practice.

## **2.5 Gaps in Existing Drone-Based Remote Sensing Literature**

Although drone-based remote sensing has been widely explored for crop health monitoring, the existing literature reveals several gaps that limit its relevance for tropical agricultural systems. These gaps relate to research focus, methodological consistency, validation under real farming conditions, and practical integration into routine agricultural decision-making.

One major gap concerns the limited focus on tropical-specific conditions. Many drone-based crop monitoring studies are conducted in temperate regions with relatively stable weather patterns and well-structured farming systems (Torres-Sánchez et al., 2014). While findings from these studies demonstrate technical feasibility, their applicability to tropical agriculture remains uncertain. Tropical environments present unique challenges related to rapid crop growth, high humidity, frequent rainfall, and heterogeneous cropping patterns, which are often insufficiently addressed in experimental designs (Atzberger, 2013; Zhang and Kovacs, 2012).

A second gap relates to inconsistent methodologies across studies. The literature shows wide variation in sensor types, flight parameters, image processing workflows, and vegetation indices used to assess crop health. This lack of standardization complicates comparison of results across studies and limits the development of transferable guidelines for drone deployment in agriculture (Mulla, 2013). Few studies explicitly justify their methodological choices in relation to environmental or crop-specific conditions common in tropical systems.

The validation of drone-derived indicators under farmer-managed conditions represents another important gap. Many studies validate drone imagery against ground measurements collected under controlled or research-managed settings. While such validation is necessary, it does not fully capture the variability and management practices present in real-world tropical farming systems. As a result, the reliability of drone-based crop health indicators for routine farm decision-making remains insufficiently demonstrated (Bendig et al., 2014).

Economic and operational considerations are also underrepresented in the literature. Most studies emphasize technical performance metrics, such as correlation between vegetation indices and biomass, while giving limited attention to cost, labor requirements, and ease of use (Lowenberg-DeBoer and Erickson, 2019). For smallholder-dominated tropical agriculture, these factors strongly influence adoption decisions. The absence of detailed economic analysis limits understanding of whether drone-based monitoring can be sustainably integrated into existing agricultural practices (Tsouros et al., 2019).

Another gap concerns integration with advisory and management systems. Drone-based remote sensing studies often present crop health maps without examining how such information is interpreted by farmers, extension agents, or agronomists. Few studies assess how drone-derived insights translate into management actions, such as targeted fertilization or pest control, particularly in tropical contexts where access to inputs and advisory services may be constrained (Mulla, 2013).

Finally, there is a lack of long-term and comparative studies. Most research is based on single-season experiments or short-term trials, which limits assessment of consistency across seasons and varying climatic conditions. Long-term evaluations are necessary to understand how drone-based crop health monitoring performs under interannual variability common in tropical agriculture (Atzberger, 2013).

These gaps indicate that while drone-based remote sensing shows promise for crop health monitoring, existing research provides an incomplete basis for large-scale adoption in tropical agriculture. Addressing these limitations requires studies that prioritize tropical conditions, methodological transparency, economic feasibility, and integration with practical farm management systems. Identifying these gaps provides the foundation for the methodological approach adopted in this review. These gaps are summarized in Table 2 and inform the analytical focus adopted in the subsequent sections of this review.

**Table 2. Key gaps in drone-based remote sensing literature for crop health monitoring in tropical agriculture**

Identified gap	Description of gap in existing literature	Implications for tropical agricultural applications
Limited focus on tropical-specific conditions	Many drone-based crop monitoring studies are conducted in temperate or controlled environments, with limited emphasis on tropical climates characterized by high humidity, frequent rainfall, and rapid crop growth	Findings may not translate directly to tropical systems where environmental conditions affect data quality and flight feasibility
Methodological inconsistency across studies	Wide variation exists in sensor selection, flight altitude, image overlap, preprocessing steps, and vegetation indices, often without clear justification	Lack of standardization limits comparability of results and development of transferable best practices
Limited validation under farmer-managed conditions	Validation is commonly performed under experimental or research-managed plots rather than real farming systems	Reliability of drone-derived indicators for routine farm decision-making remains uncertain
Insufficient attention to operational feasibility	Many studies emphasize technical performance while giving limited attention to labor requirements, data processing burden, and ease of deployment	Operational constraints may limit adoption in resource-constrained tropical agriculture
Weak integration with advisory and management systems	Drone outputs are often presented as maps or indices without examining how information is interpreted or used by farmers and extension services	Crop health information may not translate into actionable management decisions
Lack of long-term and multi-season assessments	Most studies are based on single-season trials or short-term experiments	Performance under interannual climatic variability common in tropical regions remains unclear
Limited economic evaluation	Few studies examine costs relative to benefits for small-scale or mixed farming systems	Adoption decisions cannot be fully assessed without understanding economic viability

### 3. Methodology

#### 3.1 Review Design

This study adopts a structured review approach to synthesize existing research on drone-based remote sensing for crop health monitoring in tropical agriculture. The review emphasizes comparative analysis and contextual evaluation rather than quantitative aggregation. This approach is appropriate given the diversity of study designs, sensors, crops, and analytical methods reported in the literature on drone-based agricultural monitoring (Zhang & Kovacs, 2012; Mulla, 2013). The objective is to assess how drone technologies have been applied, the

types of crop health indicators examined, and the constraints affecting their use in tropical environments.

This review does not employ meta-analysis techniques. The reviewed studies vary widely in terms of sensor specifications, flight parameters, spatial resolution, and validation methods, which makes statistical synthesis inappropriate.

### **3.2 Data Sources and Search Strategy**

The literature search was conducted using Scopus, Web of Science, and Google Scholar, which provide broad coverage of peer-reviewed research in remote sensing, precision agriculture, and environmental monitoring. Searches were performed using combinations of keywords including “drone,” “UAV,” “remote sensing,” “crop health,” “vegetation indices,” and “tropical agriculture.”

Conference proceedings and journal articles were prioritized due to their relevance to applied remote sensing research.

### **3.3 Inclusion and Exclusion Criteria**

Studies were included in the review if they met the following criteria. First, the study examined the use of drones or unmanned aerial vehicles for crop health assessment or related vegetation monitoring. Second, the study was a peer-reviewed journal or refereed conference proceeding. Third, the study provided sufficient methodological detail regarding sensors, data acquisition, or analytical techniques. Studies were excluded if they focused exclusively on satellite remote sensing, addressed drone technology without application to agriculture, or lacked adequate description of data collection and analysis. Publications centered on non-agricultural applications of drones were also excluded.

### **3.4 Study Selection and Scope**

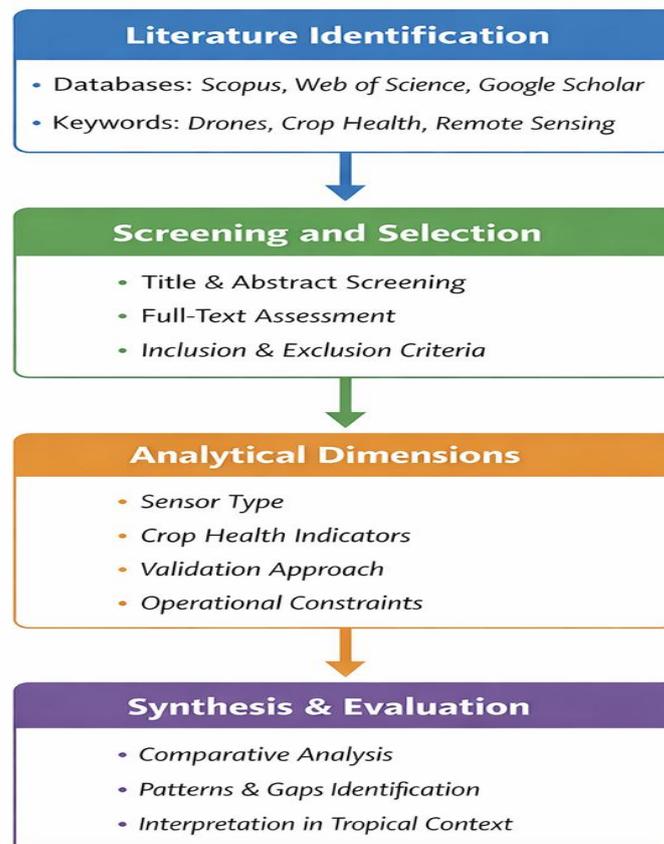
Relevant studies were identified through title screening, abstract review, and full-text assessment based on the predefined inclusion criteria. The reviewed literature includes experimental field studies, methodological assessments, and review papers that examine the use of drone-based remote sensing for crop health monitoring in tropical or comparable agricultural environments. The selected studies reflect a range of crops, sensor types, and analytical approaches, providing a basis for comparative synthesis across different applications and contexts.

### **3.5 Analytical Approach**

The selected studies were analyzed using a qualitative comparative framework. Each study was examined across four dimensions. First, the sensor type and data characteristics, including RGB, multispectral, or thermal imagery. Second, the crop health indicators and vegetation indices used. Third, the validation approach, including ground measurements or yield data. Fourth, the reported constraints, including environmental, operational, or institutional factors relevant to tropical agriculture. This comparative structure ensured consistent evaluation across studies while allowing differences in crop type, environmental conditions, and management context to be explicitly considered.

### 3.6 Methodological Limitations

Several limitations should be acknowledged. The review is constrained by the limited number of studies explicitly focused on tropical agriculture. As a result, some findings are informed by studies conducted in comparable subtropical environments. In addition, variation in methodological reporting limits direct comparison across studies. These limitations reflect both the current state of published evidence and the scope deliberately defined for this review. Figure 1 presents a conceptual overview of the review workflow adopted in this study. It illustrates the sequence of literature identification, screening, and selection, followed by the analytical dimensions used to synthesize evidence on drone-based remote sensing for crop health monitoring. The figure clarifies how diverse studies were evaluated in a consistent manner while accounting for differences in environmental and operational context.



**Fig 1. Conceptual workflow for literature identification and analytical synthesis of drone-based remote sensing studies.**

## 4. Results and Evaluation

This section synthesizes findings from the reviewed literature, focusing on how drone-based remote sensing has been applied to crop health monitoring in tropical and comparable agricultural environments. The results are organized around sensor usage, crop health indicators, validation approaches, and reported operational performance.

### 4.1 Sensor Types and Data Characteristics

Across the reviewed studies, three primary sensor types are used for crop health assessment: RGB, multispectral, and thermal sensors. RGB cameras are the most widely used due to their low cost and ease of deployment. Studies report that high-resolution RGB imagery supports assessment of canopy structure, plant density, and visible stress symptoms, particularly in early growth stages (Bendig et al., 2014).

Multispectral sensors are commonly used to capture reflectance in red, green, blue, and near-infrared bands. These sensors enable calculation of vegetation indices that are sensitive to chlorophyll content and canopy vigor. Several studies report that multispectral drone imagery provides higher sensitivity to crop stress than RGB data alone, especially under nutrient or water-limited conditions (Hunt et al., 2010; Zhang & Kovacs, 2012). Thermal sensors are less frequently used but are applied in studies focused on plant water stress. Thermal imagery captures canopy temperature variation, which is linked to transpiration and stomatal conductance. Reviewed studies indicate that thermal data can support identification of water-stressed zones within fields, although interpretation is influenced by environmental conditions and sensor calibration (Mulla, 2013).

#### **4.2 Vegetation Indices and Crop Health Indicators**

Vegetation indices derived from drone imagery are central to crop health assessment. The Normalized Difference Vegetation Index is the most frequently reported indicator, used as a proxy for green biomass and canopy vigor (Hunt et al., 2013). Studies show that NDVI maps generated from drone data reveal spatial variability at resolutions far finer than those provided by satellite imagery (Bendig et al., 2014). Other indices, including green-based and red-edge indices, are used in a smaller number of studies to capture specific crop responses. These indices are reported to be sensitive to changes in chlorophyll concentration and leaf structure, which are relevant for detecting nutrient stress and early disease symptoms (Hunt et al., 2010). However, index selection varies widely across studies, and few papers provide systematic comparison of index performance under tropical conditions.

#### **4.3 Validation Against Ground Measurements**

Most reviewed studies validate drone-derived indicators using ground-based measurements such as biomass, leaf area, or yield. Moderate to strong correlations are reported between vegetation indices and biomass under controlled conditions. Bendig et al. (2014) report that crop surface models derived from drone imagery correlate well with measured biomass in cereal crops. However, validation approaches differ substantially across studies. Some rely on limited sampling points, while others use plot-level averages. Few studies assess validation under farmer-managed conditions, and even fewer evaluate consistency across seasons. This variability limits the ability to generalize reported performance of drone-based indicators to diverse tropical farming systems (Mulla, 2013).

#### **4.4 Operational Performance and Limitations**

Operational performance is reported unevenly across studies. Several papers note that drone-based monitoring enables rapid data collection and flexible scheduling, which supports timely assessment of crop health (Salamí et al., 2014). However, operational challenges are also reported, including limited flight duration, sensitivity to weather conditions, and high data processing requirements (Zhang and Kovacs, 2012). Studies conducted in humid or cloudy environments report increased difficulty in maintaining consistent illumination and reflectance

conditions. These factors affect data quality and complicate comparison across flight dates. While preprocessing techniques are used to address these issues, their effectiveness varies and is not always clearly documented (Atzberger, 2013).

#### 4.5 Comparative Summary

Overall, the reviewed literature indicates that drone-based remote sensing provides detailed field-level information that complements conventional crop monitoring approaches. The strongest results are reported under controlled experimental conditions with careful sensor calibration and validation. Evidence from operational, farmer-managed tropical systems remains limited. Key characteristics of drone-based crop health monitoring applications are summarized in Table 1.

**Table 1. Summary of drone-based remote sensing applications for crop health monitoring in tropical and comparable agricultural systems**

Application focus	Sensor type commonly used	Crop health indicators assessed	Validation approach reported	Key observations from the literature
Canopy vigor and biomass assessment	RGB and multispectral sensors	Canopy cover, vegetation indices such as NDVI	Ground measurements of biomass or area	High-resolution imagery captures within-field variability not detectable through satellite data
Detection of nutrient stress	Multispectral sensors	Changes in spectral reflectance and vegetation indices	Comparison with nutrient status from field sampling	Spatial patterns of nutrient stress can be identified at early growth stages under controlled conditions
Monitoring water stress	Thermal sensors, of sometimes combined with multispectral	Canopy temperature and temperature-based stress indicators	Soil moisture or plant water status measurements	Thermal imagery supports identification of water-stressed zones but is sensitive to environmental conditions
Assessment of pest or disease impact	RGB and multispectral sensors	Changes in canopy color, structure, and reflectance	Visual assessment and plot-level comparisons	Early field symptoms are detectable when image quality and timing are appropriate
Spatial variability analysis for site-specific management	Multispectral sensors	Vegetation index maps at high spatial resolution	Field observations or yield maps	Drone data supports targeted field management by revealing fine-scale variability

Application focus	Sensor type commonly used	Crop health indicators assessed	Validation approach reported	Key observations from the literature	
Methodological evaluation studies	RGB, multispectral, and thermal sensors	Image metrics and index performance	quality and experimental validation	Controlled experimental validation	Performance depends strongly on flight planning, calibration, and data preprocessing

## 5. Discussion

The reviewed literature indicates that drone-based remote sensing offers clear advantages for crop health monitoring in tropical agriculture, particularly in terms of spatial detail and flexibility of data collection. Compared with conventional monitoring approaches, drones enable field-level observation of crop variability at resolutions that are not achievable through satellite imagery under persistent cloud cover. This capability is especially relevant in tropical systems, where rapid crop development and heterogeneous field conditions demand timely and localized assessment.

At the same time, the discussion of results highlights that the effectiveness of drone-based monitoring depends strongly on operational context. Studies reporting strong relationships between drone-derived indicators and crop health metrics are typically conducted under controlled conditions with careful flight planning, sensor calibration, and validation protocols. These conditions are not always representative of farmer-managed tropical systems, where variability in management practices, field access, and technical capacity can influence data quality and interpretation. As a result, reported performance should be interpreted as indicative rather than universally applicable.

Sensor selection emerges as a key consideration in tropical crop monitoring. Multispectral sensors are frequently associated with improved sensitivity to crop stress, particularly when vegetation indices are used to assess canopy vigor and nutrient status. However, the literature also shows that RGB imagery can provide useful information for crop assessment when combined with appropriate analytical techniques. This suggests that sensor choice should be guided by monitoring objectives, environmental conditions, and resource availability rather than by technological preference alone (Peña et al., 2013).

Environmental conditions common in tropical agriculture present persistent challenges for drone deployment. Variable illumination, high humidity, and frequent rainfall affect both flight feasibility and data consistency. While preprocessing techniques can reduce some of these effects, they add complexity to data workflows and increase technical requirements. These constraints limit the practicality of frequent drone-based monitoring in many tropical settings and underscore the need for simplified operational approaches.

The discussion also reveals a gap between data generation and decision support. Many studies focus on producing vegetation maps or indices without examining how this information is translated into management actions. In tropical agriculture, where access to inputs and advisory services may be limited, the value of drone-derived information depends on its integration into existing decision-making processes. Without clear pathways from data to action, the benefits of high-resolution monitoring may remain unrealized (Eastwood et al., 2017).

Economic and institutional factors further shape the role of drones in tropical agriculture. Equipment costs, regulatory requirements, and the need for technical expertise constrain adoption, particularly among small-scale farmers. The literature provides limited evidence on cost-effectiveness or long-term sustainability, making it difficult to assess whether drone-based monitoring can move beyond research applications into routine agricultural practice.

Overall, the reviewed evidence suggests that drone-based remote sensing has the potential to complement existing crop health monitoring approaches in tropical agriculture, rather than replace them. Its value lies in targeted applications where fine-scale spatial information is needed and where operational conditions support reliable data collection. Realizing this potential will require research that prioritizes tropical-specific conditions, practical validation under real farming systems, and integration with advisory frameworks that support actionable decision-making.

## **6. Conclusion**

This paper reviewed existing research on the use of drone-based remote sensing for crop health monitoring in tropical agriculture, with attention to sensor technologies, analytical approaches, and operational constraints. The synthesis shows that drones can provide detailed, field-level information on crop condition that complements conventional monitoring methods, particularly in environments where satellite observations are limited by cloud cover and coarse spatial resolution.

The reviewed literature indicates that drone-derived imagery supports assessment of canopy vigor, spatial variability, and early crop stress when appropriate sensors, flight planning, and data processing procedures are applied. Multispectral and thermal data are frequently associated with improved sensitivity to physiological stress, while RGB imagery remains useful for structural and visual assessment under suitable conditions. These capabilities are relevant for tropical agriculture, where rapid crop development and heterogeneous field conditions require timely and localized monitoring.

At the same time, the findings highlight important limitations that constrain broader adoption. Environmental conditions common in tropical regions affect data quality and flight feasibility. Operational demands related to data processing, technical expertise, and equipment maintenance remain significant barriers. In addition, many studies are conducted under experimental conditions, leaving uncertainty about performance and usefulness in farmer-managed systems.

The analysis also reveals that the value of drone-based monitoring depends on its integration into practical decision-making processes. High-resolution maps and vegetation indices alone do not improve outcomes unless they inform management actions that are feasible within local agronomic and institutional contexts. Economic considerations, regulatory frameworks, and access to advisory services therefore play a critical role in determining whether drone-based approaches can be sustained beyond research settings.

Overall, drone-based remote sensing should be viewed as a complementary tool for crop health monitoring in tropical agriculture. Its effective use requires alignment with environmental conditions, operational capacity, and management objectives. Future research would benefit from greater focus on tropical-specific validation, simplified workflows, and evaluation under

real farming conditions. Such efforts are necessary to clarify the practical role of drones in supporting crop health monitoring and agricultural decision-making in tropical systems.

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