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Application of Drone Remote Sensing Technology in Agricultural Pest Monitoring and Its Challenges

Yimin Gao[1,2], **Wujun Xi**[2]*

[1]School of Geography, Yunnan Normal University, Kunming 650500, China
[2]School of Resources, Environment and Chemistry, Chuxiong Normal University, Chuxiong 675000, China

**Author to whom correspondence should be addressed.*

Abstract: With the increasing global population and mounting pressures on agricultural production, precise pest monitoring has become a critical factor in ensuring food security. Traditional monitoring methods, often inefficient, struggle to meet the demands of modern agriculture. Drone remote sensing technology, leveraging its high efficiency and flexibility, demonstrates significant potential in pest monitoring. Equipped with multispectral, hyperspectral, and thermal infrared sensors, drones can rapidly cover large agricultural fields, capturing high-resolution imagery and data to detect spectral variations in crops. This enables effective differentiation between healthy and infested plants, facilitating early pest identification and targeted control. This paper systematically reviews the current applications of drone remote sensing technology in pest monitoring by examining different sensor types and their use in monitoring major crop pests and diseases. It also discusses existing challenges, aiming to provide insights and references for future research.

Keywords: Drone remote sensing; Pest monitoring; Crops; Applications

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1. Introduction

With the continuous growth of the global population and increasing pressures on agricultural production, pest management and monitoring have become crucial components in safeguarding food security [1]. Pests not only directly impact crop yields but may also trigger ecological imbalances. Therefore, timely and accurate pest monitoring and identification are essential for achieving precision agriculture and sustainable development. However, traditional pest monitoring methods—such as manual field inspections and sample collection—are often time-consuming and inefficient, failing to meet the demands of modern agriculture [2]. In recent years, drone remote sensing technology has garnered significant attention due to its efficiency, accuracy, and operational flexibility. Equipped with various sensors, drones can rapidly cover extensive agricultural areas, capturing high-resolution imagery and data. By analyzing spectral signatures across different bands, they enable early pest detection and distinguish between healthy and infected crops. This approach substantially enhances the speed and precision of agricultural pest monitoring. This paper categorizes research progress in two key dimensions: (1) the types of sensors integrated with drones; (2) applications in monitoring major crop pests. It systematically reviews current advancements in drone-based remote sensing for pest surveillance, analyzes existing challenges, and provides insights to inform future research directions.

2. Principles of crop pest monitoring using drone remote sensing technology

The underlying principle of drone-based crop pest monitoring stems from physiological and morphological changes in plants under pest stress, which alter their spectral reflectance characteristics. When crops are infested, significant changes occur in leaf cellular structure, chlorophyll content, and canopy water status—modifying their optical properties, particularly in terms of wavelength absorption and reflection. These variations lead to detectable fluctuations in spectral parameters [3]. The interaction between crops and pests can be assessed by monitoring electromagnetic wave properties. Pest infestation causes abnormal reflectance patterns in specific spectral bands, serving as early indicators of plant health deterioration. Leveraging this principle, drones equipped with multispectral and thermal infrared sensors capture pest-induced spectral variations. Multispectral sensors collect data across multiple bands (visible, near-infrared, and mid-infrared), enabling precise identification of plant physiological status [4]. Thermal infrared sensors detect surface temperature anomalies that reveal stress or damage symptoms. During data processing, vegetation indices and machine learning algorithms are integrated to achieve accurate pest identification and quantitative assessment. This approach not only facilitates rapid acquisition of comprehensive crop health data but also significantly enhances the efficiency and precision of pest control measures.

3. Categorization of crop pest monitoring based on different sensor types

3.1. Multispectral drone remote sensing technology

As shown in **Table 1**, the measurement indicators for crop pest monitoring using multispectral drone technology include: nitrogen content, water status, coverage rate, leaf area index (LAI), biomass, and pest stress levels. The spectral bands acquired by these sensors typically cover regions from visible light to infrared. Equipped with multispectral sensors, drones capture reflectance data from multiple discrete spectral bands to analyze physiological and biochemical changes in vegetation caused by pests/diseases. This technology is characterized by: a limited number of spectral bands; relatively lower spectral resolution; capability for rapid acquisition over large agricultural areas; output typically presented as stepped or sawtooth-shaped spectral curves. In agricultural pest monitoring, this approach demonstrates significant cost advantages: (1) Lower equipment costs make it suitable for preliminary large-scale field screening; (2) Enables early disease detection through vegetation indices like NDRE (Normalized Difference Red Edge Index).

Recent years have witnessed extensive research on multispectral drone applications in crop protection: Zhao *et al.* [5] developed early detection methods for rice sheath blight, demonstrating high sensitivity of multispectral data during initial infection stages; Jia [6] successfully monitored maize leaf spot disease progression, with particularly notable detection efficacy during disease expansion phases. While advantageous for cost-effective large-area monitoring, the technology's limited spectral resolution constrains its capability to differentiate complex disease types.

Table 1. Characteristics of crop diseases identified by multispectral techniques

Sensor type	Measurement index	Characteristics	Advantages	Disadvantages	References
Multispectral camera	Nitrogen, water, cover, leaf area, biomass, pest and disease stress, etc	Small number of bands; Suitable for rapid scanning of a large area of farmland	Low cost; Early detection of diseases; It is suitable for the preliminary screening of large areas of farmland	Unable to distinguish complex disease types; Limited detection accuracy	[7]

3.2. Hyperspectral drone remote sensing technology

As shown in **Table 2**, hyperspectral sensors monitor the degree of crop damage caused by pests and diseases through measurement indicators including coverage rate, leaf area index (LAI), biomass, yield potential, and pest/disease stress levels. These sensors cover visible light, near-infrared, and short-wave infrared bands with hundreds of continuous narrow bands, featuring extremely high spectral resolution that can capture subtle changes in plant health status such as leaf pigment degradation, water stress, and secondary metabolite accumulation.

The core advantage of this technology in crop pest monitoring lies in its high-dimensional spectral information capability, which can sensitively identify differences between healthy and diseased tissues and even distinguish different disease types. For example: Yuan *et al.* [8] successfully differentiated wheat stripe rust from powdery mildew using hyperspectral analysis technology while monitoring disease severity levels; their discrimination model achieved over 80% overall accuracy with recognition accuracy reaching 95% for leaves showing more than 20% disease coverage ratio; Wu [9] investigated classification methods for Masson pine pest damage levels using hyperspectral technology. Hyperspectral imaging systems on drones have been applied to early disease warning systems for cash crops such as tea plantations [10] and orchards [11]. However, this technology faces challenges including large data volume requirements, high processing complexity, expensive sensor costs, and susceptibility to environmental noise factors (such as illumination variations and background soil interference) during field applications; these issues require integration with dimensionality reduction algorithms and model optimization to improve practical utility.

Table 2. Characteristics of crop diseases identified by hyperspectral techniques

Sensor type	Measurement index	Characteristics	Advantages	Disadvantages	References
Hyperspectral camera	Coverage, leaf area, biomass, yield, pests and diseases, damage stress, etc.	Hundreds of continuous bands; Ability to capture subtle spectral differences	Accurately identify disease types; Suitable for complex disease analysis	Equipment is expensive; Complex data processing	[7]

3.3. Thermal imaging technology

As shown in **Table 3**, thermal infrared sensors monitor crop stress indicators such as temperature and moisture levels under pest/disease pressure by detecting anomalies in canopy temperature and water status. The principle relies on elevated surface temperatures caused by impaired plant transpiration processes. Drones equipped with thermal infrared cameras can rapidly identify field hotspots, proving particularly effective for coupled drought stress-disease monitoring while maintaining operational capability during nighttime conditions. Several researchers have investigated thermal imaging applications for pest/disease monitoring: Oerke *et al.* [12] conducted quantitative analysis using digital infrared thermography on apple scab-infected leaves; Belin *et al.* [13] demonstrated superior detection performance of thermal imaging compared to fluorescence imaging for apple scab diagnosis; Schmitz *et al.* [14] successfully identified nematode-infected beet fields through canopy temperature differentials.

While thermal imaging has been applied across multiple crop-pest systems, its relatively low spatial resolution limits single-plant scale disease differentiation and makes it susceptible to ambient temperature variations. Consequently, this technology is typically employed as a complementary approach alongside other sensor systems.

Table 3. Characteristics of crop diseases identified by thermal imaging technology

Sensor type	Measurement index	Characteristics	Advantages	Disadvantages	References
Thermal infrared camera	Temperature, moisture, etc.	Depending on the heat radiation emitted by the object, it can work at night.	It is suitable for detecting local temperature anomalies caused by diseases	Low resolution; Affected by ambient temperature	[7]

3.4. LiDAR technology

LiDAR (Light Detection and Ranging) works by emitting laser pulses and receiving reflected signals to generate high-precision 3D point cloud data that quantifies changes in canopy structural parameters caused by pests/diseases, such as leaf area index (LAI), canopy height, and porosity metrics—making it particularly suitable for analyzing morphological changes induced by diseases. As shown in **Table 4**, LiDAR measures crop indicators, including plant height, leaf area index (LAI), biomass, etc., to identify pest/disease damage since infestation often leads to leaf loss or branch deformation that can be detected through point cloud density variations or vertical profile analysis; it can even identify concealed pests. The technology's main advantages are its strong penetration capability that captures internal canopy structure information regardless of lighting conditions. Current applications include forest health monitoring using drone-mounted LiDAR systems, while agricultural uses mainly involve fusion with multispectral data to build multi-dimensional stress diagnosis models, like combining NDVI with canopy height to predict wheat lodging risk [15].

However, limitations include high data acquisition costs, complex processing requirements, difficulty directly distinguishing different pest/disease types without relying on machine learning algorithms like point cloud segmentation networks to extract deep features, resulting in relatively high technical barriers.

Table 4. Characteristics of lidar to identify crop diseases

Sensor type	Measurement index	Characteristics	Advantages	Disadvantages	References
Laser radar	Plant height, leaf area, biomass, etc.	The laser pulse is emitted, and the reflection time is measured. Generate 3D spatial information	Provide vegetation structure change information; Suitable for analysis of morphological changes caused by diseases	High cost; Complex data processing	[7]

4. Major crop pest monitoring classification

4.1. Rice

As shown in **Table 5**, the main diseases and pests affecting rice include rice blast, sheath blight, brown planthopper, false smut, bacterial leaf streak, and bacterial leaf blight. Rice pest monitoring primarily uses drones equipped with various sensors combined with multi-source data fusion to achieve early identification and dynamic tracking of major diseases such as rice blast and sheath blight as well as insect pests like brown planthopper. Due to the complex paddy field environment, monitoring technologies need to balance both spectral sensitivity and environmental interference resistance. Multispectral and hyperspectral remote sensing analyzes leaf pigment content, including chlorophylls, carotenoids, and water absorption characteristics, to detect reflectance anomalies under disease stress conditions. For example, in early rice blast infection stages, visible band reflectance increases significantly while near-infrared reflectance decreases due to cellular structure damage. Hyperspectral data enables early warning through continuous narrow-band analysis. Liu *et al.* [16] achieved grading detection of rice leaf blast severity using hyperspectral imaging combined with LMPSO-SVM models; Kang [17] applied hyperspectral detection technology to qualitatively identify major rice blast types (leaf blast, panicle blast, grain blast) in naturally infected northern field rice, aiming to improve disease impact monitoring assessment capabilities. Future trends focus on multi-sensor collaboration such as combining drone hyperspectral with ground IoT sensors along with deep learning model optimization to enhance monitoring accuracy and timeliness under complex paddy field conditions [18].

Table 5. Main pest and disease types and detection methods of rice

Crop	Main types of pests and diseases	UAV monitoring method	References
Rice	Rice blast disease, sheath blight disease, rice planthopper, rice curl disease, stripe disease, bacterial leaf blight disease, etc.	Multispectral/hyperspectral sensors: identify victim features such as leaf discoloration and crimp, and assess pest and disease distribution. Thermal infrared camera: monitor pest activity in hot areas.	[19]

4.2. Wheat

As shown in **Table 6**, the main diseases/pests affecting wheat include rust, powdery mildew, *Fusarium* head blight (FHB), aphids, wheat spider mites, and crown rot. The wheat disease/pest monitoring system primarily relies on hyperspectral early diagnosis combined with satellite large-scale screening, focusing particularly on stripe rust, FHB, and aphids. Hyperspectral technology enables latent disease detection by quantifying foliar biochemical parameters (chlorophyll degradation/water loss) through continuous spectral features across red-edge/short-wave infrared (SWIR) bands [20]. For instance, stripe rust infection causes a sharp reflectance decline at the red-edge region while FHB exhibits unique absorption troughs at SWIR bands. Thermal imaging distinguishes biotic/abiotic stresses via canopy temperature anomalies. Feng *et al.* [21] developed wheat powdery mildew severity models by acquiring flowering, grain-filling stage data via UAV-mounted multispectral, thermal cameras. Extracted vegetation indices/texture features, canopy temperatures were processed through multiple linear regression/random forest algorithms, demonstrating random forest's superiority in multi-source data fusion modeling. Guo [22] established stripe rust monitoring frameworks integrating multi-source imaging data across leaf/canopy/regional scales, fusing spectral-spatial features to improve surveillance accuracy at varying scales. The key challenge lies in overlapping spectral signatures among different diseases (e.g., rust vs. powdery mildew), necessitating optimized feature band selection/machine learning classifier development.

Table 6. Main pest and disease types and detection methods of wheat

Crop	Main types of pests and diseases	UAV monitoring method	References
Wheat	Rust, powdery mildew, scab, aphid, wheat spider, stem rot, etc	Multispectral sensors: detect leaf disease spots (such as rust spore piles) and pest density. Thermal infrared camera: identify abnormal areas of plant temperature.	[23]

4.3. Corn

As shown in **Table 7**, the main diseases, pests affecting corn include corn borer (*Ostrinia furnacalis*), cotton bollworm (*Helicoverpa armigera*), armyworm (*Mythimna separata*), rust (*Puccinia sorghi*), brown spot (*Bipolaris maydis*), and northern corn leaf blight (*Exserohilum turcicum*). Corn disease/pest monitoring primarily employs multispectral rapid screening combined with structural parameter analysis, focusing on major threats like corn borer, fungal leaf spots, and fall armyworm (*Spodoptera frugiperda*) [24]. Multispectral technology utilizes vegetation indices (e.g., MSAVI/NDRE) to track chlorophyll variation for rapid pest localization. For instance, corn borer stem boring causes NDRE values to decrease by 20–30%. Synthetic Aperture Radar (SAR) monitors canopy density changes via microwave scattering characteristics, where C-band data identifies lodging, insect-damage-induced biomass loss. Tian *et al.* [25] developed a segmented hybrid distance method using hyperspectral imaging to determine optimal wavebands through corn stalk analysis, then applied threshold segmentation, mathematical morphology techniques, achieving rapid, accurate, non-destructive borer detection. Xing [26] implemented hyperspectral imaging for corn borer identification employing calibration/mask preprocessing followed by principal component analysis (PCA) for feature extraction, enabling precise nondestructive inspection. However, dense corn canopies severely obstruct optical remote sensing, requiring integrated microwave, LiDAR observations. Current multi-source data fusion algorithms exhibit insufficient efficiency, necessitating future lightweight edge computing devices enabling real-time field processing (2025/05/23) and early warning systems.

Table 7. Main pest and disease types and detection methods of maize

Crop	Main types of pests and diseases	UAV monitoring method	References
Corn	Corn borer, cotton bollworm, armyworm, rust, brown spot, large spot, etc.	Multispectral/hyperspectral imagery: Distinguishing corn borer larvae gnawing holes from healthy leaves. Lidar: Scans for changes in plant height and monitors growth suppression caused by pests	[27]

4.4. Cotton

As shown in **Table 8**, the main diseases/pests affecting cotton include cotton bollworm (*Helicoverpa armigera*), cotton aphid (*Aphis gossypii*), spider mites (*Tetranychus* spp.), Fusarium wilt (*Fusarium oxysporum*), Verticillium wilt (*Verticillium dahliae*), and mirid bugs (*Apolygus lucorum*). Cotton disease/pest monitoring primarily relies on multispectral and thermal imaging technologies, focusing on major threats such as cotton bollworm, Verticillium wilt, and spider mites [28]. Multispectral remote sensing enables target identification through near-infrared band reflectance reduction (caused by leaf damage due to pests) and red-edge band shifts (resulting from chlorophyll anomalies caused by diseases). Thermal imaging captures early physiological responses via canopy temperature gradient anomalies (Verticillium wilt areas show a temperature increase of 1–2°C).

However, since thermal imaging is susceptible to environmental factors (wind speed, sunlight), it requires joint analysis with spectral data [29]. Chen [30] analyzed the spectral characteristics of Verticillium wilt-infected cotton leaves and canopies using hyperspectral technology, discussing their relationship with disease severity, and established a disease identification model along with a severity inversion model. Chen [31] combined ground spectrometers with drone remote sensing technology, intending to analyze the spectral characteristics of cotton under different disease severity levels through laboratory and field experiments. They extracted sensitive bands and constructed disease severity estimation models using multiple regression modeling methods, thereby providing a basis for Verticillium wilt monitoring and control. Synthetic Aperture Radar (SAR) has limited application in cotton fields, but its penetration capability can be used to monitor soil moisture anomalies (such as reduced water absorption caused by root diseases). The advantage of drone-based cotton disease/pest monitoring lies in the flexibility of UAV platforms for rapid acquisition of high-resolution data. The limitation is the high similarity between spectral features of different cotton diseases/pests (e.g., Verticillium wilt vs. nutrient deficiency disorders). To improve classification accuracy, the incorporation of texture features (such as Gray-Level Co-occurrence Matrix [GLCM]) is necessary [32].

Table 8. Main types and detection methods of cotton pests and diseases

Crop	Main types of pests and diseases	UAV monitoring method	References
Cotton	Cotton bollworm, cotton aphid, red spider, Fusarium wilt, verticillium wilt, blind stink bug, etc.	Multi-spectral band combination: B3-5-8 band (550nm, 656nm, 800nm) combined with DVI index to accurately identify verticillium wilt area. RGB camera: captures red spots on leaves caused by starspiders	[33]

4.5. Other crops pest/disease monitoring classification

For cash crops (such as tea plants and fruit trees) and protected agriculture crops (such as tomatoes and cucumbers), pest disease monitoring technologies are more scenario-specific. In tea plantations, drone-based hyperspectral technology monitors tea green leafhopper damage through red-edge band reflectance anomalies while combining canopy temperature data to distinguish between insect damage and drought stress [10]. In orchards, pest disease monitoring relies on hyperspectral-multispectral fusion technology. For example, Citrus Huanglongbing causes canopy height reduction and chlorophyll fluorescence attenuation. Lan *et al.* [34] used drone-based hyperspectral remote sensing to monitor citrus orchards by classifying through spectral processing combined with machine learning models to evaluate Huanglongbing detection feasibility. Vanegas *et al.* [35] developed an early detection model for grapevine leafroll disease by integrating hyperspectral, multispectral, and RGB sensor data that could identify leaf spectral characteristic changes caused by root system damage while establishing a Digital Vigor Model (DVM) to quantify disease severity levels. In protected agriculture, machine vision technologies such as RGB imaging, multispectral cameras identify diseases including powdery mildew, gray mold through texture analysis combined with color space transformation while integrating IoT sensors for real-time environmental condition monitoring including temperature, humidity, and pathogen transmission conditions [36]. Common challenges across cash, protected crops include accurate pest/disease identification, monitoring efficiency improvement, environmental impact mitigation during data collection/cost-effective system operation simplicity assurance [37].

5. Technical limitations and future directions of drone-based pest monitoring

Although drone technology demonstrates advantages such as high efficiency and wide coverage in agricultural pest/disease monitoring, it still faces multiple challenges:

Current technical limitations include high costs such as expensive multispectral sensors, maintenance fees, complex data processing requirements, insufficient environmental adaptability, unstable operation under severe weather conditions like strong winds or rain, short battery life, limiting multi-sensor coordinated collection, resulting in single-dimensional pest identification capabilities [38]. Additionally, algorithm universality remains inadequate; models are easily affected by crop growth stages and environmental changes, leading to significant accuracy drops during cross-regional applications, while farmers' difficulties operating professional analysis software further constrain technology implementation [39]. At the policy level, regional differences in drone flight regulations lack standardized data sharing mechanisms also hinder large-scale adoption.

Future development should focus on algorithm optimization multi-source data fusion such as improving feature extraction capabilities under complex scenarios through deep learning combining satellite remote sensing ground sensors establishing dynamic monitoring networks simultaneously building unified pest spectrum databases industry standards promoting modular hardware design will become key factors driving technological popularization With interdisciplinary collaboration policy support drone technology is expected overcome current bottlenecks providing core driving force agricultural digitization sustainable development.

6. Conclusion

Drone remote sensing technology has demonstrated significant advantages in crop pest/disease monitoring. By equipping multispectral, hyperspectral, thermal infrared LiDAR, and other sensors, drones can efficiently capture crop physiological morphological changes, achieving early identification and precise localization. However, this technology still faces challenges, including environmental interference, complex data processing, relatively high costs, and limited large-scale promotion and application. Future research should focus on optimizing sensor technologies and algorithms, improving early disease identification accuracy, promoting multi-source data fusion, and artificial intelligence integration, achieving intelligent warning management, reducing technological costs, facilitating adoption by small and medium farms, strengthening interdisciplinary cooperation, and establishing comprehensive agricultural remote sensing monitoring systems.

Disclosure statement

The authors declare no conflict of interest.

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