Application of Multispectral Imaging for Coffee Agriculture

Luiz H. Mormille, Marcelo Ono and Renato Vicente

January 26, 2026

Executive Summary

Multispectral imagery acquired from satellites and unmanned aerial vehicles (UAVs) has emerged as a powerful tool for monitoring crop health and supporting precision agriculture. In coffee production, where yield, quality, and profitability are highly sensitive to diseases, pests, nutrient availability, and water stress, timely and spatially resolved information is particularly valuable. This white paper reviews the current scientific evidence supporting the use of multispectral imaging for coffee agriculture, with the objective of assessing technical feasibility and reducing scientific risk.

Across a wide range of applications —including disease detection (e.g., coffee leaf rust and Cercospora leaf spot), pest monitoring (e.g., coffee leaf miner and nematodes), detection of invasive plants, nutrient deficiency assessment, canopy vigor analysis, yield estimation, and water stress detection —the literature consistently demonstrates that multispectral data captures physiologically meaningful signals that are often detectable earlier and more reliably than conventional RGB imagery. For several high-impact use cases, multispectral approaches have already reached a level of maturity suitable for operational deployment, while others are strongly supported by mechanistic understanding and cross-crop validation.

The analysis presented here shows that the primary barrier to large-scale adoption of multispectral solutions in coffee production is no longer scientific feasibility. Instead, remaining challenges relate to data availability, temporal consistency and integration into practical agronomic decision workflows. These challenges are characteristic of scale-up phases in data-driven industries and represent opportunities for differentiation rather than fundamental limitations of the technology.

Overall, the evidence indicates that multispectral imaging is a validated and economically relevant foundation for coffee crop monitoring. The pathway from research to impact is now defined less by discovery and more by execution —specifically, the ability to deploy multispectral sensing reliably, repeatedly, and at scale to support actionable decision-making in real-world coffee production systems.

Contents

1 Introduction

Coffee production faces a unique combination of agronomic, economic, and operational challenges. Perennial crop structure, multi-year yield cycles, strong sensitivity to climate variability, and high exposure to diseases and pests make coffee particularly vulnerable to delayed or imprecise management decisions. At the same time, coffee is a high-value crop in which relatively small improvements in yield stability, input efficiency, or quality can translate into substantial economic gains for producers. These characteristics make coffee an ideal candidate for precision-agriculture approaches based on remote sensing and data-driven decision support.

Over the past decade, multispectral imagery acquired from satellites and unmanned aerial vehicles (UAVs) has repeatedly demonstrated the ability to detect agronomically relevant signals in coffee plantations. Numerous studies have shown that multispectral measurements—particularly those incorporating red-edge and near-infrared bands—are sensitive to changes in plant physiology associated with diseases, pest pressure, nutrient and water stress, canopy vigor, and yield potential. In many cases, these signals can be detected before visual symptoms become evident in standard RGB imagery, enabling earlier intervention and more targeted management practices.

For coffee specifically, the scientific literature provides growing evidence that multispectral analysis can support the monitoring of major diseases such as coffee leaf rust and Cercospora leaf spot, key pests such as the coffee leaf miner, and a range of stress factors related to nutrition and water availability. Beyond stress detection, multispectral data have also been successfully applied to structural and phenological assessments, including plant counting, canopy density estimation, vigor zoning, flowering intensity analysis, and yield prediction. Together, these applications address many of the most critical decision points in coffee production, from fertilization and irrigation planning to pest and disease control and harvest forecasting.

Importantly, the primary limitation preventing widespread adoption of these techniques is no longer scientific feasibility. The underlying biophysical relationships between spectral reflectance and plant condition are well established, supported by both field-based spectroradiometric measurements and operational multispectral imaging systems. The remaining challenges lie in scalable deployment: ensuring consistent data acquisition under real field conditions, building robust models that generalize across varieties, regions, and seasons, and integrating analytical outputs into practical farm decision workflows. Addressing these challenges is largely an engineering, data, and operational problem rather than a scientific one.

This white paper surveys the current state of multispectral imaging applications in coffee production, with a focus on evidence that reduces scientific and technical risk. By synthesizing results from UAV and satellite-based studies, we aim to demonstrate that multispectral analysis is a mature and validated tool for coffee agriculture. The goal is not to propose new algorithms, but to assess what has already been proven, identify remaining gaps toward large-scale deployment, and clarify how these technologies can be translated into reliable, economically meaningful solutions for coffee producers.

2 Multispectral vs. RGB Imagery for Coffee Agriculture

Remote sensing in agriculture often begins with conventional RGB imagery because it is inexpensive, visually intuitive, and widely available across consumer drones and cameras. However, RGB imagery measures only a narrow subset of the electromagnetic spectrum—approximately three broad bands in the visible range (red, green, and blue). Multispectral imaging extends beyond this limitation by capturing reflectance in additional, carefully selected wavelength bands, typically including regions outside human vision such as the violet, near-infrared (NIR) and often one or more red-edge bands. This difference is not merely incremental: it changes what can be measured about plant physiology and therefore what can be inferred about crop condition, stress, and productivity.

2.1 What RGB measures (and why that is limiting)

RGB imagery records how bright a surface appears in three broad visible channels. In practical terms, it is a proxy for "what the plant looks like" to the human eye. This is useful for identifying macroscopic symptoms—for example, severe yellowing, defoliation, necrotic patches, or structural damage. Yet many agronomically important processes begin as physiological changes that precede visible symptoms. Photosynthetic efficiency, chlorophyll concentration, internal leaf structure, and canopy water status can change substantially before they produce a clear color shift or texture pattern that an RGB camera can reliably detect.

There are several structural limitations of RGB imagery in coffee production:

- **Spectral ambiguity:** Different stressors (nutrient deficiency, water stress, disease onset, pest pressure) can produce visually similar signs such as mild chlorosis or reduced vigor. RGB alone often cannot distinguish causes because it lacks access to diagnostic spectral regions sensitive to plant biochemistry.
- **Late detectability:** Many problems become visible only after damage has progressed, at which point intervention may be less effective or more costly, leading to substantial crop losses.
- **Sensitivity to illumination and viewing geometry:** RGB values are strongly influenced by sunlight intensity, shadows, canopy bidirectional reflectance effects, and camera exposure settings. This complicates quantitative comparisons over time and across *talhões*, unless extensive radiometric normalization is performed.
- **Weak physical linkage to plant physiology:** RGB channels are not designed around specific absorption features of vegetation. As a result, RGB-derived metrics can correlate with plant condition but often with lower robustness across varieties, seasons, and sites.

While advanced computer vision methods can extract useful information from RGB (e.g., stand counting, canopy cover estimation, and visible symptom recognition), RGB is fundamentally constrained in its ability to measure early, subtle, and physiologically meaningful signals.

2.2 What multispectral measures (and why it is more powerful)

Multispectral sensors measure reflectance in multiple discrete wavelength bands, typically including: (i) visible bands (blue/green/red), (ii) **near-infrared (NIR)**, and often (iii) **red-edge** bands (a narrow region between red and NIR) and (iv) **violet** bands.

These additional bands are critical because vegetation has characteristic spectral behavior driven by plant biochemistry and leaf structure:

- **Chlorophyll absorption in the red region:** Healthy leaves strongly absorb red light due to chlorophyll. When chlorophyll concentration decreases (often linked to nutrient stress, disease, or senescence), red reflectance increases.
- **High reflectance in NIR due to leaf internal structure:** Healthy vegetation reflects strongly in NIR because of scattering within leaf mesophyll structures. Damage to leaf cellular structure, loss of turgor, or reduced leaf area typically decreases NIR reflectance.
- **The red-edge transition as an early stress indicator:** The red-edge is highly sensitive to changes in chlorophyll content and can detect subtle physiological variation earlier than visible color changes. This region is particularly valuable for early detection of stress in crops.

Because multispectral sensors capture bands that are directly linked to plant physiology, multispectral imagery supports **quantitative, biophysically meaningful** assessment rather than only visual interpretation. In practice, this enables stronger and more generalizable inference about crop condition, particularly for early-stage stress.

2.3 Why multispectral can detect issues earlier than RGB

Many coffee-relevant problems begin as disruptions to photosynthesis, transpiration, or nutrient transport. These disruptions alter spectral reflectance patterns in NIR and red-edge before they produce obvious changes in leaf color or canopy appearance. For instance:

- **Disease onset** can reduce chlorophyll and alter leaf structure, affecting red absorption and NIR scattering before lesions become visually apparent.
- **Pest pressure** (e.g., leaf miner damage) can reduce photosynthetically active tissue and change canopy vigor signatures, which are often visible earlier in NIR-based metrics.
- **Water stress** alters leaf water content and canopy structure, impacting reflectance patterns and vegetation index dynamics even when the canopy still appears green to an RGB camera.
- **Nutrient stress** (especially nitrogen deficiency) reduces chlorophyll concentration and can be detected through red-edge-sensitive indices that respond before strong yellowing develops.

This earlier detectability is central to the operational value proposition. Earlier detection supports earlier and more targeted intervention, improving the probability of preserving yield and quality while reducing unnecessary blanket applications of pesticides, fungicides, or fertilizers.

2.4 Vegetation indices

A major advantage of multispectral imaging is that it enables robust vegetation indices that are strongly linked to plant condition. Indices combine bands to cancel out some illumination effects while emphasizing vegetation-specific spectral behavior. For example, indices that use red and NIR bands quantify canopy greenness and vigor, while indices that incorporate red-edge can be more sensitive to chlorophyll variation.

In an operational setting, indices provide a compact representation of crop condition that can be mapped spatially across *talhões* and tracked temporally across the season. This is especially important for coffee because within-field heterogeneity can be large due to terrain, soil variability, plant age, *cultivar* differences, irrigation distribution, and management history.

Compared to RGB-only metrics, multispectral indices typically offer:

- **Greater sensitivity to subtle stress** (especially via red-edge and NIR).
- **Improved stability across lighting variation** when combined with appropriate calibration and normalization.
- **Better transferability** across farms and seasons because indices reflect plant biophysics rather than camera-dependent color responses.

2.5 Causal interpretability: multispectral supports diagnosis, not only detection

For farm decision-making, detecting "something is wrong" is less valuable than identifying *what is likely wrong* and where intervention is needed. RGB-based approaches often rely on visible symptoms that can be confounded and late. Multispectral imagery supports more causal interpretability because different stress factors can produce different patterns of change across visible, red-edge, and NIR bands, especially when analyzed over time. This substantially reduces the "science risk", since the signal is measurable, and the remaining challenge is calibration and operational workflow integration.

2.6 Operational advantages for coffee: from field scouting to scalable monitoring

The practical advantages of multispectral imaging in coffee production extend beyond improved detectability. They directly enable scalable monitoring across large areas and repeated acquisition over time:

- **Spatial targeting:** Multispectral maps can identify management zones, allowing interventions (spraying, fertilization, irrigation adjustments) to be localized to affected areas rather than applied uniformly.
- **Temporal monitoring:** By acquiring imagery repeatedly, producers can track the evolution of stress signals, verify intervention outcomes, and identify recurring patterns linked to soil or terrain.

- **Consistency and standardization:** Multispectral systems are designed for quantitative measurement, and with appropriate radiometric calibration they support more consistent comparisons across dates than standard RGB cameras.
- **Integration into decision workflows:** Multispectral outputs are naturally compatible with actionable layers (vigor maps, stress alerts, yield risk maps) that can be integrated into agronomic recommendations and farm management systems.

These operational capabilities are particularly relevant in coffee because of large plantation sizes, terrain-driven variability, and the high cost of delayed interventions. When combined with UAV flexibility (high-resolution, on-demand acquisition) and satellite scalability (broad coverage, frequent revisit), multispectral imaging provides a pathway from research demonstrations to economically meaningful farm deployment.

3 Proven Multispectral Applications for Coffee

3.1 Disease Detection and Monitoring in Coffee

Plant diseases are among the most economically damaging factors in coffee production, directly affecting leaf area, photosynthetic capacity, flowering, and ultimately yield and bean quality. From a remote sensing perspective, diseases alter plant biochemistry, internal leaf structure, and canopy architecture. These changes produce characteristic spectral responses that can be detected using multispectral imagery, often before severe visual symptoms are apparent in RGB images [1].

Over the past decade, multiple independent studies have demonstrated that multispectral data acquired from satellites, UAVs, and proximal sensors can reliably detect, monitor, and quantify major coffee diseases. Collectively, this body of work establishes that disease-related spectral signals are measurable, repeatable, and agronomically meaningful [2]. The remaining challenges are therefore operational rather than scientific.

3.1.1 Coffee Leaf Rust (*Hemileia vastatrix*

Coffee leaf rust is the most extensively studied coffee disease in the context of remote sensing and provides the strongest evidence base for multispectral monitoring. Infection by *Hemileia vastatrix* reduces chlorophyll concentration, disrupts leaf internal structure, and induces premature defoliation, all of which have direct spectral consequences in the visible, red-edge, and near-infrared regions.

Satellite-based multispectral studies using Sentinel-2 and Landsat-class sensors have demonstrated that vegetation indices derived from red, red-edge, and NIR bands can discriminate rust infection levels with accuracies exceeding those achievable with RGB imagery alone [3, 4]. Infected coffee canopies exhibit increased reflectance in the visible bands, coupled with altered NIR responses associated with loss of healthy foliage and canopy vigor. Importantly, several works report that multispectral indices enable differentiation between infection severity levels, supporting not only detection but also disease quantification [1, 5].

UAV-based studies further reinforce these findings at higher spatial resolution, showing that multispectral imagery can map within-field variability of rust incidence and severity at the scale of management zones [1]. Compared to RGB-based approaches, multispectral methods consistently demonstrate higher robustness across illumination conditions and stronger correlation with ground-assessed disease metrics. RGB imagery has been shown to detect rust symptoms once visual lesions are present [6], but multispectral data provides earlier and more stable indicators linked to physiological stress rather than late-stage appearance.

3.1.2 Cercospora Leaf Spot

Cercospora leaf spot causes localized necrosis and progressive loss of photosynthetically active leaf area. Although coffee-specific multispectral studies are more limited than for rust, the physiological mechanisms of Cercospora infection are well understood and consistent across crops. Infection leads to pigment degradation, tissue collapse, and expansion of necrotic lesions, all of which produce strong spectral contrast between healthy and diseased tissue.

Multispectral UAV studies in other crops, notably sugar beet, have demonstrated high-accuracy detection and quantification of Cercospora leaf spot using combinations of visible, red-edge, and near-infrared bands combined with vegetation indices and machine learning models [7]. These studies show that multispectral features outperform single-band or RGB-only approaches in estimating disease incidence, disease severity, and disease progression over time [8]. Given the similarity of leaf-level physiological responses to Cercospora infection across plant species, these results are directly transferable to coffee.

3.1.3 Phoma and Other Foliar Fungal Diseases

Phoma leaf spot and related fungal diseases affect coffee leaves by inducing localized lesions, tissue necrosis, and in some cases premature leaf drop. Existing studies in coffee using RGB imagery and deep learning have demonstrated that visible symptoms can be detected and classified once lesions are well developed. These results provide strong supporting evidence that disease-specific spatial patterns are present in canopy imagery [9].

From a multispectral perspective, the same physiological effects responsible for RGB-detectable lesions—loss of chlorophyll, disruption of leaf structure, and reduced leaf water content—are expected to generate stronger and earlier spectral responses outside the visible range. Evidence from multispectral and hyperspectral studies in other crops confirms that fungal leaf diseases can be detected through changes in red-edge position, NIR reflectance, and shortwave infrared responses linked to tissue dehydration [8].

3.1.4 Bacterial Blight and Related Diseases

Beyond fungal pathogens, multispectral imagery has also been successfully applied to bacterial diseases in coffee. Longitudinal satellite-based studies have shown that vegetation indices derived from multispectral time series correlate strongly with both incidence and severity of bacterial blight in commercial coffee fields [10]. These studies demonstrate that disease progression can be monitored spatially and temporally, and that disease-favorable microclimatic zones within plantations can be identified using a combination of spectral and thermal information.

3.2 Pest Detection and Monitoring in Coffee

Insect pests and soil-borne pathogens represent a persistent and spatially heterogeneous source of yield loss in coffee production. Unlike many foliar diseases, pest damage is often indirect: insects and nematodes disrupt photosynthesis, transpiration, nutrient uptake, and canopy integrity rather than immediately producing visually distinctive symptoms. This characteristic makes pest monitoring particularly well suited to multispectral remote sensing, which captures physiological stress responses even when visible damage is subtle or spatially fragmented.

3.2.1 Coffee Leaf Miner (*Leucoptera coffeella*

The coffee leaf miner is one of the most economically significant pests in coffee production, causing necrosis, premature leaf fall, and substantial reduction in photosynthetic capacity. From a spectral perspective, leaf miner infestation directly reduces healthy leaf area and alters pigment concentration, producing characteristic changes in visible reflectance and near-infrared scattering.

Multispectral UAV studies have demonstrated that vegetation indices derived from visible and near-infrared bands can reliably differentiate healthy coffee leaves from those infested by leaf miner, even at early infestation stages. In these studies, indices such as NDVI, GNDVI, and related formulations consistently show lower values in infested plants, reflecting reduced chlorophyll content and canopy vigor [11–13].

More recently, satellite-based studies using Sentinel-2 imagery have confirmed that coffee leaf miner infestation can be detected and mapped at regional scale. These works report strong statistical relationships between infestation intensity measured in the field and spectral indices derived from combinations of visible and NIR bands, with classification accuracies approaching operational thresholds for decision support. The development of pest-specific spectral indices and the integration of machine learning classifiers further improve discrimination performance, demonstrating that orbital multispectral data can support scalable pest monitoring across large coffee-producing regions [14].

3.2.2 Mites (*Oligonychus* spp. and related species)

Mite infestation in coffee primarily affects leaf physiology by damaging chloroplasts, disrupting photosynthesis, and altering transpiration rates. While mites are small and difficult to observe directly from aerial imagery, their physiological impact on leaves is substantial and well documented at the anatomical and biochemical levels.

Physiological studies show that mite attack leads to destruction of chloroplast structures and localized reductions in photosynthetic efficiency, even before severe visual bronzing or necrosis develops. These changes directly affect spectral reflectance in the visible and near-infrared regions, particularly through reduced NIR scattering associated with internal leaf damage [15].

Although coffee-specific multispectral detection studies for mites remain limited, analogous results from other crops and the strong mechanistic linkage between mite damage and spectral response support the feasibility of multispectral monitoring.

3.2.3 Nematodes

Plant-parasitic nematodes represent a distinct class of pests, as they attack the root system rather than the canopy. Nevertheless, nematode infestation produces clear above-ground physiological effects, including nutrient deficiencies, reduced plant growth, chlorosis, and general vigor decline. These secondary effects are detectable through multispectral imagery.

Studies combining multispectral UAV imagery, satellite data, and machine learning models have demonstrated the ability to estimate physiological parameters of coffee plants grown under different nematode management treatments. Multispectral reflectance data have been successfully linked to variations in chlorophyll content, plant height, canopy dimensions, and branch development, providing indirect but actionable indicators of nematode stress [16].

In addition, multispectral satellite imagery has been used to map spatial patterns of nutrient imbalance in nematode-infested coffee plantations, highlighting strong correlations between red-edge and near-infrared bands and deficiencies in key macro- and micronutrients. These results confirm that nematode presence can be inferred through its impact on plant nutrition and physiology rather than through direct detection of the organism itself [17].

3.3 Detection and Mapping of Invasive Plants (Weeds)

Invasive plants (plantas daninhas) represent a persistent challenge in coffee production systems, competing with coffee plants for water, nutrients, and light, while also increasing pest, disease pressure and operational costs. Weed infestation is typically spatially heterogeneous, making blanket chemical or mechanical control inefficient and environmentally undesirable. These characteristics make weed detection and mapping particularly well suited to multispectral remote sensing.

From a spectral perspective, weeds often differ from coffee plants in leaf structure, pigment composition, phenology, and growth dynamics. These differences produce measurable contrasts in visible, red-edge, and near-infrared reflectance, especially when analyzed across time. Multispectral imagery therefore enables discrimination between coffee canopy and invasive vegetation, even when visual differences in RGB imagery are subtle or confounded by illumination effects.

Coffee-specific studies using UAV multispectral imagery have demonstrated the feasibility of identifying weed-infested zones within plantations [18]. Vegetation indices derived from red, red-edge, and near-infrared bands have been shown to highlight areas where understory or inter-row vegetation exhibits spectral signatures distinct from coffee plants, enabling spatial mapping of weed pressure and supporting site-specific weed management strategies.

Beyond coffee, extensive evidence from other crops —including maize, soybean, cotton, lettuce and rice —demonstrates that multispectral imagery combined with machine learning classifiers can accurately detect, classify, and map invasive plant species at both field and regional scales [19–23]. These studies consistently report improved discrimination performance when multispectral data are used instead of RGB alone, especially when red-edge and near-infrared bands are included. The physiological and structural mechanisms underlying weed–crop spectral separability are largely crop-independent, supporting direct transferability of these methods to coffee production systems.

Operationally, multispectral weed detection enables precision weed control by identifying infested zones, reducing herbicide use, lowering operational costs, and mitigating environmental impact. When integrated with UAV-based high-resolution mapping, multispectral imagery provides a scalable and low scientific-risk foundation for invasive plant management in coffee agriculture.

3.4 Nutrient Deficiency Detection and Monitoring

Nutrient availability is a primary driver of coffee growth, yield stability, and long-term plantation health. Deficiencies in macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), as well as key micronutrients including boron (B) and magnesium (Mg), produce characteristic physiological and biochemical responses in plants. These responses directly affect leaf pigment composition, internal leaf structure, water relations, and canopy development, all of which influence spectral reflectance.

Nutrient deficiencies are systemic rather than localized, making them particularly well suited to multispectral remote sensing. The scientific basis for nutrient detection via spectral data is well established across crops, growth conditions, and sensing platforms. In the context of coffee, existing studies combined with extensive cross-crop evidence demonstrate that multispectral imagery provides a feasible and scalable approach for diagnosing nutrient stress.

3.4.1 Nitrogen Deficiency

Nitrogen is a fundamental component of chlorophyll, amino acids and proteins, and nitrogen deficiency is therefore strongly associated with reductions in chlorophyll concentration and photosynthetic capacity. Spectrally, this manifests as increased reflectance in the visible region (particularly green and red wavelengths) and reduced absorption in the red-edge region, with secondary effects in near-infrared reflectance due to changes in canopy structure.

Nitrogen deficiency is the most extensively studied nutrient stress in remote sensing literature. Multispectral and hyperspectral studies across a wide range of crops have consistently shown strong correlations between nitrogen content and vegetation indices such as NDVI, GNDVI, NDRE, and related formulations. These relationships have been validated using satellite imagery, UAV-mounted multispectral cameras, and proximal sensors, often with high coefficients of determination and low prediction error [24–27].

In coffee specifically, multispectral UAV imagery has been shown to discriminate fertilization treatments and nutrient management regimes with higher accuracy than traditional agronomic measurements alone. Studies using low-cost multispectral sensors demonstrate that nitrogen-related stress patterns can be detected over extended vegetative periods, supporting both diagnosis and monitoring of fertilization practices [28, 29].

From an operational standpoint, nitrogen deficiency represents a very low-risk and high-impact application for multispectral imagery in coffee production, with mature methodologies and well-understood spectral behavior.

3.4.2 Phosphorus Deficiency

Phosphorus plays a central role in energy transfer, nucleic acid synthesis, and membrane structure. Phosphorus deficiency affects plant growth from early developmental stages, often resulting in stunted growth, reduced leaf expansion, and, in some species, accumulation of anthocyanin pigments that produce reddish or purplish discoloration.

Spectrally, phosphorus deficiency influences reflectance primarily in the visible and red-edge regions, with more subtle effects than nitrogen deficiency. Hyperspectral and multispectral studies across crops such as oilseed rape, maize, and tomato demonstrate that phosphorus stress can be detected and differentiated when appropriate spectral features and multivariate models are used [30, 31].

Cross-crop UAV multispectral studies show that phosphorus deficiency can be identified with high accuracy, particularly when combined with time-series analysis and machine learning approaches [29]

3.4.3 Potassium Deficiency

Potassium is critical for osmoregulation, enzyme activation, and stomatal function. Potassium deficiency often leads to impaired water regulation, marginal leaf necrosis, and increased susceptibility to drought and other stresses. Unlike nitrogen and phosphorus, potassium deficiency can significantly affect leaf water content and internal cellular structure, producing distinctive spectral responses.

Multispectral UAV and satellite studies in maize and other crops demonstrate that potassium deficiency can be detected and quantified using vegetation indices that incorporate visible and near-infrared bands [32]. These studies report strong correlations between spectral indices and foliar potassium concentration, as well as clear differentiation between severe deficiency and adequate nutrient supply [30, 31].

Importantly, potassium deficiency has been shown to influence near-infrared reflectance more strongly than nitrogen deficiency, due to its impact on leaf turgor and internal scattering properties. This makes potassium stress particularly amenable to multispectral sensing, even with relatively low-cost sensors [33].

3.4.4 Micronutrients and Combined Nutrient Stress

Micronutrient deficiencies, including boron and magnesium, also produce measurable spectral effects, primarily through their influence on chlorophyll synthesis, pigment balance, and leaf structural integrity. Magnesium deficiency, for example, directly affects chlorophyll molecules, leading to interveinal chlorosis, while boron deficiency disrupts cell wall formation and meristem development.

While individual micronutrient deficiencies can be challenging to distinguish using simple vegetation indices alone, recent studies demonstrate that multispectral and hyperspectral data combined with machine learning models can successfully detect and segment nutrient-related leaf anomalies. Deep learning approaches applied to multi-channel spectral imagery have shown particular promise in identifying subtle and spatially distributed nutrient stress symptoms that are difficult to capture with RGB imagery [28].

3.5 Growth, Vigor, Yield Estimation, and Water Stress

Beyond disease, pest, and nutrient monitoring, multispectral imagery has demonstrated strong capability in quantifying fundamental biophysical and phenological attributes of coffee crops. Parameters such as plant growth, canopy vigor, stand density, fruit development, and water stress are central to production forecasting and management decisions. Importantly, these attributes exhibit consistent and measurable spectral responses, making them particularly amenable to remote sensing.

In coffee production systems, where yield variability is driven by a combination of plant physiology, phenology, and environmental conditions, multispectral imagery provides a scalable means of capturing spatial and temporal variability that is impractical to measure through ground sampling alone.

3.5.1 Growth and Canopy Vigor Monitoring

Plant growth and vigor are closely linked to chlorophyll concentration, leaf area index, canopy volume, and photosynthetic activity. Multispectral studies in coffee consistently show that vegetation indices derived from visible, red-edge, and near-infrared bands correlate strongly with these parameters.

UAV-based multispectral studies in coffee plantations demonstrate that indices such as NDVI, GNDVI, GCI, and CVI can accurately estimate chlorophyll content and general plant health across entire fields. These indices have been shown to outperform single-band or RGB-based approaches, particularly under variable illumination and heterogeneous canopy conditions [34].

Systematic mappings of multispectral applications in Latin American coffee production further confirm that vigor-related indices are the most widely used and robust spectral indicators, with consistent application across countries, cultivars, and production systems. These studies highlight multispectral imaging as a reliable tool for phenological monitoring, detection of underperforming zones, and evaluation of management practices at plantation scale [2].

From an operational standpoint, growth and vigor monitoring represents one of the most mature and low-risk applications of multispectral imagery in coffee agriculture.

3.5.2 Stand Density and Plant Counting

Stand density and plant population directly influence yield potential and long-term plantation productivity. Traditionally, plant counting is performed manually or estimated indirectly, both of which are labor-intensive and error-prone.

Recent advances in UAV multispectral imaging combined with deep learning have demonstrated highly accurate coffee plant detection and counting across different phenological stages. Studies leveraging multispectral bands alongside RGB imagery report detection and counting accuracies exceeding 95%, with clear improvements over RGB-only approaches during non-flowering stages, where spectral contrast between coffee plants and background vegetation is reduced [35].

These results establish plant counting via multispectral UAV imagery as a feasible and scalable method for supporting yield estimation, replanting decisions, and spatially explicit management planning.

3.5.3 Yield Estimation and Production Forecasting

Yield prediction is one of the most economically valuable applications of remote sensing in coffee production. Multispectral imagery enables yield estimation by capturing both structural and physiological predictors, such as canopy volume, vegetation indices, and phenological stage.

Coffee-specific studies demonstrate that multispectral aerial imagery acquired during early phenological stages—particularly flowering—can be used to predict yield at the individual tree level [36]. Vegetation indices such as NDVI, combined with physical descriptors like canopy volume, show statistically significant correlations with final yield, enabling early-season production forecasts months before harvest [37].

At larger spatial scales, satellite-based multispectral time series have also been used to estimate regional coffee production by linking vegetation indices and phenological indicators to historical yield records. These approaches reinforce the scalability of multispectral yield estimation beyond individual farms [38].

3.5.4 Fruit Development and Ripeness Monitoring

Fruit development and ripeness are critical determinants of coffee quality and harvest timing. Multispectral UAV studies demonstrate that spectral indices can discriminate between ripeness classes and identify spatial variability in fruit maturation within fields.

Low-cost multispectral cameras mounted on UAVs have been successfully used to monitor coffee ripeness by differentiating areas suitable and unsuitable for harvest based on vegetation indices and multivariate analysis. These studies show that multispectral imagery enables non-destructive, field-wide assessment of ripeness, overcoming the limitations of manual sampling [39, 40].

3.5.5 Water Stress Detection

Water availability is a key limiting factor in coffee production, particularly under increasing climate variability. Water stress affects stomatal conductance, leaf temperature, pigment composition, and internal leaf structure, producing measurable spectral responses [41, 42].

Multispectral imagery has been widely used to detect water stress through changes in visible, red-edge, and near-infrared reflectance, often complemented by thermal data when available. Even in the absence of thermal sensors, multispectral vegetation indices have been shown to capture early stress signals associated with reduced photosynthetic efficiency and canopy vigor [43, 44].

4 Remaining Challenges and Strategic Opportunities

The evidence synthesized in the preceding sections demonstrates that multispectral imagery is a scientifically validated and agronomically relevant tool for coffee production. Across diseases, pests, nutrient deficiencies, growth monitoring, yield estimation, and water stress detection, the fundamental sensing mechanisms are well understood and repeatedly confirmed in the literature.

However, despite this strong scientific foundation, large-scale adoption of multispectral solutions in coffee agriculture remains limited. This gap is not explained by a lack of feasibility, but rather by a set of practical, operational, and organizational challenges. Importantly, these challenges also define the core opportunity space for scalable, autonomous solutions.

4.1 Data Availability and Ground Truth at Scale

One of the primary limitations across applications is the availability of high-quality, spatially explicit ground truth data. While many studies demonstrate strong correlations between spectral features and agronomic variables, they are often conducted on limited plots, specific cultivars, or single growing seasons.

In operational settings, coffee plantations exhibit significant variability in management practices, soil conditions, plant age, pruning systems, and microclimate. Collecting consistent, standardized ground truth across these dimensions is costly and logistically complex. As a result, model generalization across farms and regions remains a key challenge.

At the same time, this constraint creates a significant barrier to entry. Organizations capable of systematically pairing multispectral imagery with structured agronomic data over multiple seasons gain a durable advantage, as model performance improves primarily through data accumulation rather than algorithmic novelty.

4.2 Temporal Consistency and Time-Series Modeling

Many agronomic signals of interest—particularly those related to pests, nutrient stress, and water availability—are dynamic rather than static. Single-image analysis often captures only a snapshot of plant condition and may conflate multiple stressors.

The literature increasingly shows that temporal analysis of multispectral time series substantially improves detection robustness and interpretability. However, maintaining consistent acquisition schedules, sensor calibration, and cloud-free observations over time introduces operational complexity, especially when combining UAV and satellite data.

This challenge highlights an opportunity for systems designed around temporal continuity rather than isolated observations. Solutions that emphasize trend detection, anomaly identification, and phenology-aware modeling are better aligned with real-world agronomic decision-making.

4.3 Integration into Agronomic Workflows

Perhaps the most critical barrier to adoption is not technical but organizational. Multispectral insights only create value when they are delivered in a form that integrates naturally into existing farm decision workflows. This includes actionable recommendations, clear uncertainty communication, and alignment with operational timelines such as fertilization windows, pest control schedules, and harvest planning.

Many existing solutions fail not because the models are inaccurate, but because the outputs are disconnected from how producers and agronomists actually operate. Bridging this gap requires close collaboration with end users and a focus on decision support rather than raw analytics.

4.4 From Scientific Validation to Scalable Advantage

Taken together, the challenges outlined above do not undermine the feasibility of multispectral applications in coffee agriculture. Instead, they clarify why widespread adoption has lagged behind scientific validation. The core sensing problem has been solved; the remaining work lies in data infrastructure, system integration, and operational execution.

For organizations capable of addressing these challenges holistically, multispectral imagery represents not only a powerful diagnostic tool but a foundation for scalable, defensible agricultural intelligence systems. In this context, the opportunity is not to prove that multispectral sensing works, but to deploy it reliably, repeatedly, and at scale in real-world coffee production environments.

5 Conclusion and Outlook

This white paper reviewed the current state of multispectral imaging applications in coffee agriculture, with a focus on reducing scientific and technical uncertainty. Across diseases, pests, nutrient deficiencies, growth monitoring, yield estimation, and water stress detection, the literature provides consistent and compelling evidence that multispectral imagery captures agronomically meaningful signals linked to plant physiology and production outcomes.

For several high-impact applications—most notably coffee leaf rust, nitrogen deficiency, canopy vigor assessment, plant counting, and water stress detection—multispectral approaches have reached a level of maturity suitable for operational deployment. For others, including pest monitoring, micronutrient stress, and yield forecasting, feasibility is well supported by mechanistic understanding and cross-crop validation, with remaining limitations primarily related to data availability and system integration rather than sensing capability.

A central conclusion of this review is that the core scientific question—whether multispectral imagery can detect and monitor key drivers of coffee productivity—has largely been answered in the affirmative. The dominant challenges now lie beyond basic research. They concern consistent data acquisition, temporal modeling, and the integration of spectral insights into practical agronomic workflows. These challenges are characteristic of scale-up phases in many data-driven industries and are best addressed through engineering discipline, longitudinal data collection, and close collaboration with end users.

From a strategic perspective, this transition from scientific validation to scalable deployment defines the primary opportunity in multispectral coffee intelligence. Organizations capable of systematically combining multispectral imagery with agronomic context, historical field data, and decision-support frameworks can move beyond isolated analytics toward reliable, repeatable, and economically meaningful solutions.

Looking forward, advances in sensor availability, UAV autonomy, satellite revisit frequency, and machine learning methods—particularly those designed for time-series and multimodal data—are expected to further lower operational barriers. As these technologies mature, multispectral imaging is positioned to become a foundational layer in precision coffee agriculture, supporting more resilient production systems, optimized input use, and improved yield predictability under increasing environmental variability.

In this context, the question is no longer whether multispectral imagery can add value to coffee production, but how effectively and at what scale it can be translated into actionable intelligence. The evidence surveyed here suggests that the pathway from research to impact is clear, and that execution, rather than discovery, will determine success in the next phase of multispectral deployment in coffee agriculture.

References

[1] Analis da Silva Soares, Bruno Sérgio Vieira, Thalita Almeida Bezerra, George Deroco Martins, and Ana Carolina Silva Siquieroli. Early detection of coffee leaf rust caused by hemileia vastatrix using multispectral images. *Agronomy*, 12(12):2911, 2022.

[2] Laura Sofia Caicedo Apraez, Andrés Felipe Solis Pino, Andres Ossa, Carlos Iván Vasquez, Juan David Solarte, Efrén Venancio Ramos Cabrera, and Saul Eduardo Ruiz. Application of spectral imaging and vegetation index in latin american coffee production: A systematic mapping. *Land Degradation & Development*, 36(2):337–349, 2025.

[3] Abel Chemura, Onisimo Mutanga, and Timothy Dube. Separability of coffee leaf rust infection levels with machine learning methods at sentinel-2 msi spectral resolutions. *Precision Agriculture*, 18(5):859–881, 2017.

[4] JORGE LUIS AROCA TRUJILLO and ALEXANDER PÉREZ RUIZ. Technologies applied in the field of early detection of coffee rust fungus diseases: a review. 2023.

[5] Miryan Silva de Oliveira Pires, Marcelo de Carvalho Alves, and Edson Ampélio Pozza. Multispectral radiometric characterization of coffee rust epidemic in different irrigation management systems. *International Journal of Applied Earth Observation and Geoinformation*, 86:102016, 2020.

[6] Yakdiel Rodriguez-Gallo, Byron Escobar-Benitez, and Jony Rodriguez-Lainez. Robust coffee rust detection using uav-based aerial rgb imagery. *AgriEngineering*, 5(3):1415–1431, 2023.

[7] Abel Barreto, Facundo Ramón Ispizua Yamati, Mark Varrelmann, Stefan Paulus, and Anne-Katrin Mahlein. Disease incidence and severity of cercospora leaf spot in sugar beet assessed by multispectral unmanned aerial images and machine learning. *Plant Disease*, 107(1):188–200, 2023.

[8] BK Raghavendra et al. An efficient approach for coffee leaf disease classification and severity prediction. *International Journal of Intelligent Engineering & Systems*, 16(5), 2023.

[9] Eugenio Vocaturo et al. Phoma leaf spot disease classification and object detection in coffee plantations using yolov6 with severity estimation. *SPAST Reports*, 1(2), 2025.

[10] Diego Bedin Marin, Marcelo de Carvalho Alves, Edson Ampélio Pozza, Leônidas Leoni Belan, and Marcelo Loran de Oliveira Freitas. Multispectral radiometric monitoring of bacterial blight of coffee. *Precision agriculture*, 20(5):959–982, 2019.

[11] Luana Mendes dos Santos, Gabriel Araújo e Silva Ferraz, Diego Bedin Marin, Milene Alves de Figueiredo Carvalho, Jessica Ellen Lima Dias, Ademilson de Oliveira Alecrim, and Mirian de Lourdes Oliveira e Silva. Vegetation indices applied to suborbital multispectral images of healthy coffee and coffee infested with coffee leaf miner. *AgriEngineering*, 4(1):311–319, 2022.

[12] Luana Mendes dos Santos, Gabriel Araújo e Silva Ferraz, Nicole Lopes Bento, Diego Bedin Marin, Giuseppe Rossi, Gianluca Bambi, and Leonardo Conti. Use of images obtained by remotely piloted aircraft and random forest for the detection of leaf miner (leucoptera coffeella) in newly planted coffee trees. *Remote Sensing*, 16(4):728, 2024.

[13] Emerson Ferreira Vilela, Cileimar Aparecida da Silva, Jéssica Mayara Coffler Botti, Elem Fialho Martins, Charles Cardoso Santana, Diego Bedin Marin, Agnaldo Roberto de Jesus Freitas, Carolina Jaramillo-Giraldo, Iza Paula de Carvalho Lopes, Lucas de Paula Corrêdo, et al. Detection of coffee leaf miner using rgb aerial imagery and machine learning. *AgriEngineering*, 6(3): 3174–3186, 2024.

[14] Emerson Ferreira Vilela, Williams Pinto Marques Ferreira, Gabriel Dumbá Monteiro de Castro, Ana Luisa Ribeiro de Faria, Daniel Henrique Leite, Igor Arantes Lima, Christiano de Sousa Machado de Matos, Rogério Antonio Silva, and Madelaine Venzon. New spectral index and machine learning models for detecting coffee leaf miner infestation using sentinel-2 multispectral imagery. *Agriculture*, 13(2):388, 2023.

[15] Joel I Fahl, Rachel B Queiroz-Voltan, Maria Luiza C Carelli, Marlene A Schiavinato, Ana KS Prado, and Júlio C Souza. Alterations in leaf anatomy and physiology caused by the red mite (oligonychus ilicis) in plants of coffea arabica. *Brazilian Journal of Plant Physiology*, 19:61–68, 2007.

[16] Fernando Vasconcelos Pereira, George Deroco Martins, Bruno Sérgio Vieira, Gleice Aparecida de Assis, and Vinicius Silva Werneck Orlando. Multispectral images for monitoring the physiological parameters of coffee plants under different treatments against nematodes. *Precision Agriculture*, 23(6):2312–2344, 2022.

[17] George Deroco Martins, Maria de Lourdes Bueno Trindade Galo, Bruno Sérgio Vieira, Ricardo Falqueto Jorge, and Cinara Xavier de Almeida. Mapping nutrients content in a nematode-infected coffee plantation by empirical models derived from rapideye image. *Anuário Do Instituto de Geociências-UFRJ*, 42(3):164–177, 2019.

[18] Nicole Lopes Bento, Gabriel Araújo e Silva Ferraz, Jhones da Silva Amorim, Lucas Santos Santana, Rafael Alexandre Pena Barata, Daniel Veiga Soares, and Patrícia Ferreira Ponciano Ferraz. Weed detection and mapping of a coffee farm by a remotely piloted aircraft system. *Agronomy*, 13(3):830, 2023.

[19] Filip Feyaerts and Luc Van Gool. Multi-spectral vision system for weed detection. *Pattern Recognition Letters*, 22(6-7):667–674, 2001.

[20] Oscar Barrero and Sammy A Perdomo. Rgb and multispectral uav image fusion for gramineae weed detection in rice fields. *Precision agriculture*, 19(5):809–822, 2018.

[21] Kavir Osorio, Andrés Puerto, Cesar Pedraza, David Jamaica, and Leonardo Rodríguez. A deep learning approach for weed detection in lettuce crops using multispectral images. *AgriEngineering*, 2(3):471–488, 2020.

[22] Victor Alchanatis, Leonid Ridel, Amots Hetzroni, and Leonid Yaroslavsky. Weed detection in multi-spectral images of cotton fields. *Computers and electronics in agriculture*, 47(3):243–260, 2005.

[23] Kevin D Gibson, Richard Dirks, Case R Medlin, and Loree Johnston. Detection of weed species in soybean using multispectral digital images. *Weed Technology*, 18(3):742–749, 2004.

[24] H Noh, Qin Zhang, Shufeng Han, B Shin, and D Reum. Dynamic calibration and image segmentation methods for multispectral imaging crop nitrogen deficiency sensors. *Transactions of the ASAE*, 48(1):393–401, 2005.

[25] PS Fouche. Detecting nitrogen deficiency on irrigated cash crops using remote sensing methods. *South African Journal of Plant and Soil*, 16(2):59–63, 1999.

[26] Ji-Yan Wu, Zheng Yong Poh, Anoop C Patil, Bongsoo Park, Giovanni Volpe, and Daisuke Urano. Analysis of plant nutrient deficiencies using multi-spectral imaging and optimized segmentation model. *arXiv preprint arXiv:2507.14013*, 2025.

[27] Arief Ika Uktoro, Rengga Arnalis Renjani, Sandiaga Kusuma, Dwi Asmono, Ruli Wandri, Samsu Alam, Muchamad Nur Fanani Kramajaya, Angga Cahyo Riyanto, Teddy Suparyanto, Bens Pardamean, et al. Detecting nutrient deficiency in oil palm seedlings using multispectral uav images. *Commun. Math. Biol. Neurosci.*, 2024:Article–ID, 2024.

[28] Camila Isabel Pereira Rezende, Gleice Aparecida de Assis, George Deroco Martins, Fábio Janoni Carvalho, Miguel Henrique Rosa Franco, and Nathalia Oliveira de Araújo. Multispectral images for discrimination of sources and doses of fertilizer in coffee plants. *Revista Ceres*, 70(3):54–63, 2023.

[29] Wenbo Li, Ke Wang, Guiqi Han, Hai Wang, Ningbo Tan, and Zhuyun Yan. Integrated diagnosis and time-series sensitivity evaluation of nutrient deficiencies in medicinal plant (ligusticum chuanxiong hort.) based on uav multispectral sensors. *Frontiers in Plant Science*, 13:1092610, 2023.

[30] Guoxiang Sun, Yongqian Ding, Xiaochan Wang, Wei Lu, Ye Sun, and Hongfeng Yu. Nondestructive determination of nitrogen, phosphorus and potassium contents in greenhouse tomato plants based on multispectral three-dimensional imaging. *Sensors*, 19(23):5295, 2019.

[31] Shishi Liu, Xin Yang, Qingfeng Guan, Zhifeng Lu, and Jianwei Lu. An ensemble modeling framework for distinguishing nitrogen, phosphorous and potassium deficiencies in winter oilseed rape (brassica napus l.) using hyperspectral data. *Remote Sensing*, 12(24):4060, 2020.

[32] Renato Herrig Furlanetto, Marco Rafael Nanni, Luís Guilherme Teixeira Crusiol, Guilherme Fernando Capristo Silva, Adilson de Oliveira Junior, and Rubson Natal Ribeiro Sibaldelli. Identification and quantification of potassium (k+) deficiency in maize plants using an unmanned aerial vehicle and visible/near-infrared semi-professional digital camera. *International Journal of Remote Sensing*, 42(23):8783–8804, 2021.

[33] S Sridevy, Anna Saro Vijendran, R Jagadeeswaran, and M Djanaguiraman. Nitrogen and potassium deficiency identification in maize by image mining, spectral and true colour response. *Indian Journal of Plant Physiology*, 23(1):91–99, 2018.

[34] Natalia Arteaga-López, Carlos Delgado-Calvache, Juan-Fernando Casanova, and Cristhian Figueroa. Coffee crops analysis using uavs equipped with multispectral cameras. *Revista Facultad de Ingeniería*, 31(62), 2022.

[35] Xiaorui Wang, Chao Zhang, Zhenping Qiang, Chang Liu, Xiaojun Wei, and Fengyun Cheng. A coffee plant counting method based on dual-channel nms and yolov9 leveraging uav multispectral imaging. *Remote Sensing*, 16(20):3810, 2024.

[36] Carlos Alberto Matias de Abreu Júnior, George Deroco Martins, Laura Cristina Moura Xavier, Bruno Sérgio Vieira, Rodrigo Bezerra de Araújo Gallis, Eusimio Felisbino Fraga Junior, Rafaela Souza Martins, Alice Pedro Bom Paes, Rafael Cordeiro Pereira Mendonça, and João Victor do Nascimento Lima. Estimating coffee plant yield based on multispectral images and machine learning models. *Agronomy*, 12(12):3195, 2022.

[37] Julian Bolaños, Juan Carlos Corrales, and Liseth Viviana Campo. Feasibility of early yield prediction per coffee tree based on multispectral aerial imagery: Case of arabica coffee crops in cauca-colombia. *Remote Sensing*, 15(1):282, 2023.

[38] Marco Antonio Zanella, Rodrigo Nogueira Martins, Fábio Moreira da Silva, Luis Carlos Cirilo Carvalho, Marcelo de Carvalho Alves, and Jorge Tadeu Fim Rosas. Coffee yield prediction using high-resolution satellite imagery and crop nutritional status in southeast brazil. *Remote Sensing Applications: Society and Environment*, 33:101092, 2024.

[39] Jorge Tadeu Fim Rosas, Francisco de Assis de Carvalho Pinto, Daniel Marçal de Queiroz, Flora Maria de Melo Villar, Domingos Sarvio Magalhaes Valente, and Rodrigo Nogueira Martins. Coffee ripeness monitoring using a uav-mounted low-cost multispectral camera. *Precision Agriculture*, 23(1):300–318, 2022.

[40] Rodrigo Nogueira Martins, Francisco de Assis de Carvalho Pinto, Daniel Marçal de Queiroz, Domingos Sárvio Magalhães Valente, Jorge Tadeu Fim Rosas, Marcelo Fagundes Portes, and Elder Sânzio Aguiar Cerqueira. Digital mapping of coffee ripeness using uav-based multispectral imagery. *Computers and Electronics in Agriculture*, 204:107499, 2023.

[41] Patrícia Carvalho da Silva, Walter Quadros Ribeiro Junior, Maria Lucrecia Gerosa Ramos, Omar Cruz Rocha, Adriano Delly Veiga, Nathalia Henriques Silva, Lemerson de Oliveira Brasileiro, Charles Cardoso Santana, Guilherme Filgueiras Soares, Juaci Vitória Malaquias, et al. Physiological changes of arabica coffee under different intensities and durations of water stress in the brazilian cerrado. *Plants*, 11(17):2198, 2022.

[42] Julieta Andréa Silva de Almeida, Mary Túlia Vargas Lobato Guedes de Azevedo, Marcus Vinicius Salomon, and Priscila Fratin Medina. Water stress in germination, growth and development of coffee cultivars. *Journal of Seed Science*, 40(1):82–89, 2018.

[43] Abel Chemura, Onisimo Mutanga, and Timothy Dube. Remote sensing leaf water stress in coffee (coffea arabica) using secondary effects of water absorption and random forests. *Physics and Chemistry of the Earth, Parts a/b/c*, 100:317–324, 2017.

[44] Vinicius Silva Werneck Orlando, George Deroco Martins, EF Fraga Júnior, Aline Barrocá Marra, Fernando Vasconcelos Pereira, and M Galo. Potential of multispectral images taken by sensors embedded in uavs for monitoring the coffee crop irrigation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 10:91–96, 2023.