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REVIEW ARTICLE

Application of Spectral Imaging and Vegetation Index in Latin American Coffee Production: A Systematic Mapping

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ABSTRACT

Coffee production is a crucial economic, social, and cultural pillar in Latin America, facing numerous challenges, including integrating technological advancements such as multispectral imaging. This approach offers multiple advantages for coffee production; however, a knowledge gap in the domain is the need to methodologically review the available empirical evidence to delineate the field and the study region. Therefore, this systematic mapping aims to map the scientific corpus of multispectral imagery and vegetation index implemented in coffee production in the Latin American region. The study followed the PRISMA protocol; 42 primary studies were analyzed to identify key trends and research gaps. The main result of this research is that NDVI emerged as the most widely used spectral index, with applications in estimating critical biophysical parameters such as biomass and chlorophyll content. Other indices such as GNDVI, NDRE, and SAVI also proved valuable in assessing coffee plant health and development. There was an emerging trend to integrate multispectral imaging with machine learning techniques, promising greater accuracy in data interpretation. The study also revealed a concentration of research efforts in selected Latin American countries, particularly Brazil, indicating opportunities to expand research in other coffee-producing regions. The study's main conclusion is that multispectral imaging, mainly through vegetation index, has emerged as a valuable tool for phenological monitoring and management of coffee production, offering several advantages over traditional methods. Finally, this review contributes to the existing knowledge base and identifies future research directions for applying multispectral imagery to sustainable coffee production in Latin America.

1 | Introduction

Coffee is a drink of global importance with multiple implications. Economically, it is one of the most internationally traded agricultural commodities, second only to oil (Bozzola et al. 2021); it accounts for a daily global expenditure of US$165 million, and millions of people are involved in its purchase, from production in developing countries to consumption worldwide (Raimondo 2022). Its production and trade generate income and jobs throughout the supply chain (Kangile et al. 2021). Socially, coffee consumption is rooted in the customs and traditions of many cultures, fostering human interaction (Maspul and Almalki 2023). Numerous studies suggest that moderate coffee consumption can reduce the risk of diseases such as Parkinson's, Alzheimer's, Type 2 diabetes, certain types of cancer, and liver disease, thanks to its antioxidant and bioactive compounds (Ruggiero et al. 2021). Beyond its economic impact, coffee plays a fundamental role in the sociocultural dynamics of many societies.

The coffee production process is complex, necessitating careful management of soil fertility, irrigation, and pest control (Melke

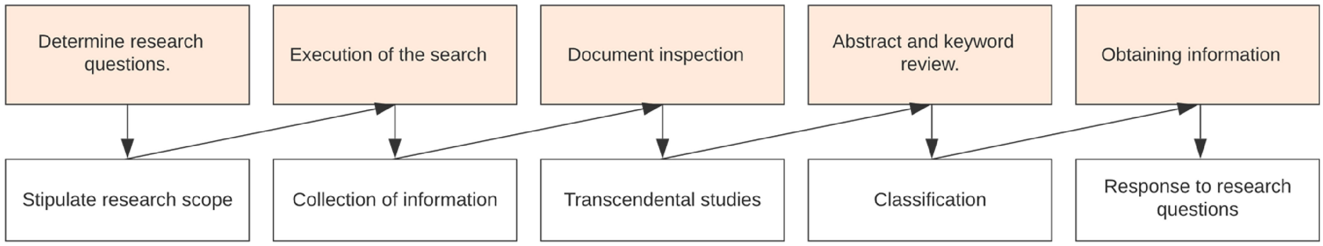

FIGURE 1 | Systematic mapping process. [Colour figure can be viewed at wileyonlinelibrary.com]

and Ittana 2014). Precision agriculture has proven invaluable in optimizing crop yields, minimizing waste, and reducing costs while maintaining high-quality production (Berrío, Mosquera, and Alzate 2015). These advanced technologies, such as soil mapping, crop monitoring, and weather forecasting, provide farmers with essential information for decision-making (Franco Castro 2023). Specifically, multispectral imaging has established itself as a widely used technology in the domain, which consists of capturing images of crops using cameras capable of detecting wavelengths of light beyond the range of human vision (Shahi et al. 2022), gaining considerable attention in the context of precision agriculture for coffee production (Lamb 2000). This technology makes it possible to identify variations in crop health, detect pests and diseases, and determine the optimal time for harvesting (Díaz García-Cervigón 2015), allowing farmers to make informed decisions on fertilization, irrigation, and pest control, among other parameters.

The Latin American coffee industry, which represents approximately 61% of world production, is one of the largest in the world (Rhiney et al. 2021). Coffee is essential to rural livelihoods, biodiversity conservation, and sustainable development in the region (Harvey et al. 2021). However, coffee production in Latin America faces numerous challenges, such as the rapid and profound biophysical changes in coffee farms and landscapes (Campuzano-Duque et al. 2021) and the recent coffee rust epidemic (Koutouleas, Collinge, and Boa 2024). Finally, another prevailing challenge in the domain is the need for research studies that provide solutions to these challenges and facilitate the improvement of producers' incomes, reducing production costs and a more significant application of innovative tools and technologies (Cristina et al. 2022; Ramirez-Gomez et al. 2022). This study primarily focuses on the latter aspect, investigating the application of multispectral imaging as a technological aid in coffee production. In this sense, multispectral images have been identified as a valuable technological resource in the Latin American and world coffee industry (Mihailova et al. 2022; Silva, Varela, and Lezama 2021).

Given the importance of multispectral imaging in coffee production, examining the empirical evidence available on this topic is imperative, especially in the Latin American context. This would facilitate a more comprehensive understanding, analysis, and application of this technological solution in various stages of the coffee production chain in the region.

Several studies have reviewed the state of the art of multispectral imaging applied to coffee and its derived aspects. For example, Hunt et al. (2020), where satellite-based approaches to mapping coffee extension are reviewed, highlight critical considerations for practical approaches and future directions for accurate and scalable coffee mapping to enable sustainable coffee production. Similarly, research by Santana et al. (2021) analyzed research trends in precision coffee farming between 2000 and 2021, with Brazilian institutions contributing the most. Joint research topics included geostatistical analysis, remote sensing, and spatial variability mapping, with an emerging trend toward machine learning and autonomous systems research. Finally, in Jorge Luis Aroca Trujillo (2023), a systematic mapping on remote sensing of coffee rust disease was executed to analyze the methods used and call for further research to advance early detection capabilities.

Despite significant research advances in this domain, there is a notable need for state-of-the-art reviews of remote sensing techniques, such as multispectral imaging applied to coffee in Latin America. This knowledge gap leads to a limited understanding of the subject, failure to see the advantages of this type of vision technique, missed research opportunities, and hindered evidence-based decision-making, a crucial aspect for farmers and coffee companies seeking to implement remote sensing technologies. Therefore, this research aims to systematically map the detailed literature of the scientific corpus of multispectral images applied to coffee trees in their various forms, such as leaf, bean, and plant. The research revealed aspects such as the vegetation index most applied to coffee, the countries where research on coffee is conducted, the Artificial Intelligence (AI) techniques applied to spectral images, and the diseases detected through these images. The results of this research are expected to contribute significantly to the existing knowledge base in this domain.

2 | Materials and Methods

The systematic mapping followed the PRISMA protocol (Pino et al. 2024) (Figure 1) and was adopted as the main methodological framework to conduct the research. The PRISMA protocol is a widely recognized tool that helps review authors accurately report their methodologies and findings. In addition, this study also incorporated specific guidelines proposed by Petersen, Vakkalanka, and Kuzniarz (2015).

The research process was executed in five distinct stages, as illustrated in Figure 1: (1) determination of research questions, (2) search for primary studies, (3) inspection of articles according to inclusion/exclusion criteria, (4) categorization of articles, and (5) extraction and mapping of collected data. It is important to note that the results of each stage served as input for the next stage, thus ensuring a continuous and coherent flow of the research process. This approach ensures the robustness and reliability of the research results.

Several technological tools were used to ensure methodological rigor and study coherence when conducting the systematic mapping. The Parsifal platform (Solis and Hurtado 2020) was used for the planning, execution, and reporting phases of the review. This platform is recognized for its superior methodological support in facilitating this type of study. R-Studio and Google Sheets were used to create graphical representations (Chang, Zhao, and Hajiyev 2019). Finally, the litsearchr tool (Grames et al. 2019) was used to determine appropriate initial or naive search terms. These tools collectively contributed to the detailed and systematic execution of the study.

2.1 | Research Questions Raised

The research questions aim to explore the scientific corpus of applying multispectral imagery to coffee crops in Latin America. Table 1 presents each of the research questions raised in this review.

2.2 | Search Strategy

A search string (Table 2) designed according to the PICOC criteria (Cabrera-Tenecela 2023) was used to collect information from bibliographic databases systematically. The scientific databases used were Dimensions AI, IEEE Xplore, ScienceDirect, Scopus, The Lens, and Web of Science. These databases were selected because they include abundant literature related to the engineering field (Solis and Hurtado 2020).

The search string was applied to each database's title, abstract, and keyword fields. The search covered all studies available up through May 2024, with no restrictions as to publication date. This methodology facilitated a thorough and up-to-date retrieval of the relevant literature in the domain.

2.3 | Methodology for Selection of Primary Studies

To establish a rigorous and systematic methodology for the review process, the guidelines outlined by Petersen et al. were followed along with the PRISMA protocol, which facilitated a comprehensive and detailed mapping of the relevant literature in the domain. Figure 2 depicts the iterative nature of the systematic mapping and shows how constant feedback is incorporated based on the results.

2.4 | Selection Criteria for Primary Studies

According to the methodologies indicated, inclusion and exclusion criteria (Table 3) were used to determine the most relevant studies for the research objectives and to address the research questions posed. A study was considered relevant if it met all the stipulated inclusion criteria. In contrast, any study that met a single exclusion criterion was omitted from the analysis. This rigorous approach ensured that only studies that met the strict inclusion criteria were considered, thus reinforcing the reliability and validity of the research. These selected studies are hereafter referred to as primary studies.

3 | Execution of Systematic Mapping

The systematic mapping was carried out rigorously and methodically, following the steps outlined by the PRISMA methodology. The process was divided into three phases (Figure 3), facilitated by the Parsifal tool.

In the initial phase, a search string was implemented in the bibliographic databases described above, which yielded 1086 records. These records included research articles, conference chapters, proceedings, and other scientific documents. Subsequently, duplicate records were eliminated, leaving 538 unique records in the various databases for review. Subsequently, the titles, abstracts, and keywords of these 538 papers were screened using the pre-established inclusion and exclusion criteria, resulting in a subset of 110 papers referred to as "primary study candidates".

The second phase consisted of a more detailed selection process. The inclusion and exclusion criteria were applied to the full text of each candidate's primary study, reducing the scientific corpus to 56 primary studies.

These 56 primary studies were then analyzed to determine the country of origin where the research was conducted. Studies

TABLE 1 | Research questions.

#	Research questions
1	What are Latin America's most used spectral indices for analyzing the coffee production process using multispectral images?
2	What kind of physiological parameters are inferred from applying multispectral imaging in the coffee production process in Latin America?
3	How is the data obtained from spectral indices through images used in the coffee production process in Latin America?
4	What types of diseases, pests, or unfavorable conditions are identified in Latin American coffee plantations using multispectral images?
5	What are the advantages and disadvantages of using spectral indices compared to other methods of sanitary evaluation in the coffee production process in Latin America?

TABLE 2 | Search string used in the review.

("Vegetation index" **OR** "Multispectral Vegetation Index" **OR** "Vegetation Indices" **OR** "multispectral image" **OR** "spectral imaging" **OR** "Hyperspectral Vegetation Index" **OR** "Greenness index" **OR** "Plant index" **OR** "Vegetative index" **OR** "Chlorophyll index" **OR** "Leaf index" **OR** "Multispectral imaging" **OR** "Vegetation index" **OR** "spectral indices" **OR** "NDVI" **OR** "Normalized Difference Vegetation Index" **OR** "GNDVI" **OR** "Green Normalized Difference Vegetation Index" **OR** "NDRE" **OR** "Normalized Difference Red Edge" **OR** "EVI" **OR** "Enhanced Vegetation Index" **OR** "SAVI" **OR** "Soil Adjusted Vegetation Index" **OR** "CRI" **OR** "Coffee Ripeness Index" **OR** "TVI" **OR** "Triangular Vegetation Index" **OR** "PSRI" **OR** "Plant Senescence Reflectance Index" **OR** "LAI" **OR** "Leaf Area Index") **AND** ("Coffee" **OR** "Coffea Canephora" **OR** "Coffea Arabica" **OR** "Coffee Beans" **OR** "Coffee Cultivation" **OR** "Coffee Production" **OR** "Coffee Plants" **OR** "Coffea Arabica" **OR** "Coffee Beans" **OR** "Coffee Cultivation")

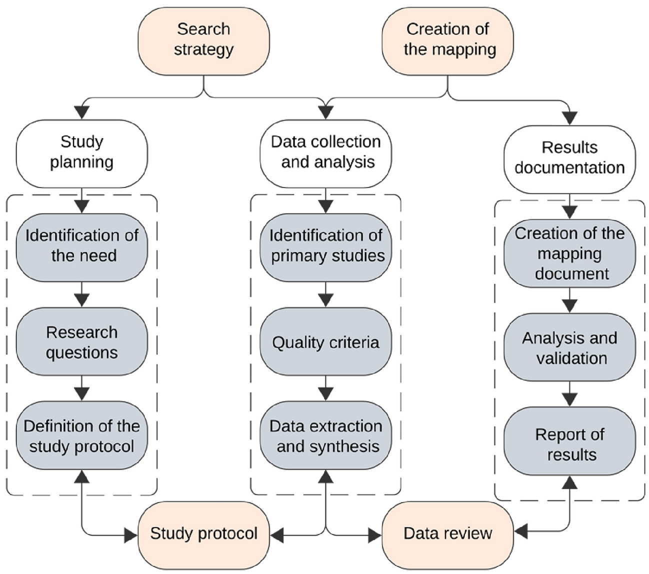

FIGURE 2 | The methodology used in the systematic mapping was suggested by Petersen, Vakkalanka, and Kuzniarz (2015). [Colour figure can be viewed at wileyonlinelibrary.com]

from Latin American countries were included in the database to answer the research questions posed. In contrast, studies from other regions were discarded, facilitating the segregation of articles according to the geographic region of Latin America, resulting in 42 articles in English and Spanish.

The last phase involved data extraction, domain characterization, and formulation of answers to the research questions.

Finally, it is essential to note that the selection procedure for duplicate studies was based on their citation indexes and the accessibility of the full text. Likewise, to preserve the integrity of the present investigation, secondary research, such as literature reviews or meta-analyses, was excluded in the data extraction phase but considered for the comparative analysis of the research results.

TABLE 3 | Inclusion and exclusion criteria for the review.

Inclusion criteria
Application of multispectral imaging in coffee production in Latin America.
The research should discuss coffee leaves and beans or their application to coffee plants.
Due to the limited availability of articles, the study must be published in English, Portuguese, or Spanish.
The research must present a well-defined and structured methodology for the study.
Specific findings or solutions related to multispectral imaging in coffee production.
Exclusion criteria
Studies do not apply vegetation indices, spectral indices, or multispectral images
Preliminary studies or those not focused on coffee production in Latin America.
Studies for which full access is unavailable and cannot be reviewed.
Research that has not undergone peer review
Publications mainly report or analyze other research results.
Studies with duplicate authorship, titles, abstracts, results, or content.

4 | Results and Analysis

The research identified 42 primary studies that constitute the scientific corpus that will be used to answer the proposed research questions.

Figure 4 shows the contributions of each scientific database, classified by primary articles, duplicate studies, and rejected studies. When analyzing the data and the contributions of each database, it is evident that Web of Science contributed the most primary articles to the study, with 17 articles representing approximately 8% of the articles found. It was followed by Scopus, which contributed 4% of the articles found, representing 12 primary studies. According to the existing literature, these two databases are predominantly used in engineering (Pino et al. 2024; Zhu and Liu 2020). Interestingly, unlike other research where the database is leading, IEEE Xplore contributed only 1 primary article and had 11 articles found (Solis and Hurtado 2020).

Q1. *What Are Latin America's Most Used Spectral Indices for Analyzing the Coffee Production Process Using Multispectral Images?*

Coffee cultivation faces numerous challenges, requiring the use of precise tools for monitoring and management (Santana et al. 2021). Consequently, studies using multispectral imagery, which employ various methodologies to examine aspects of crop health and productivity, have proliferated in the scientific corpus of the coffee sector (Parida et al. 2024). Spectral

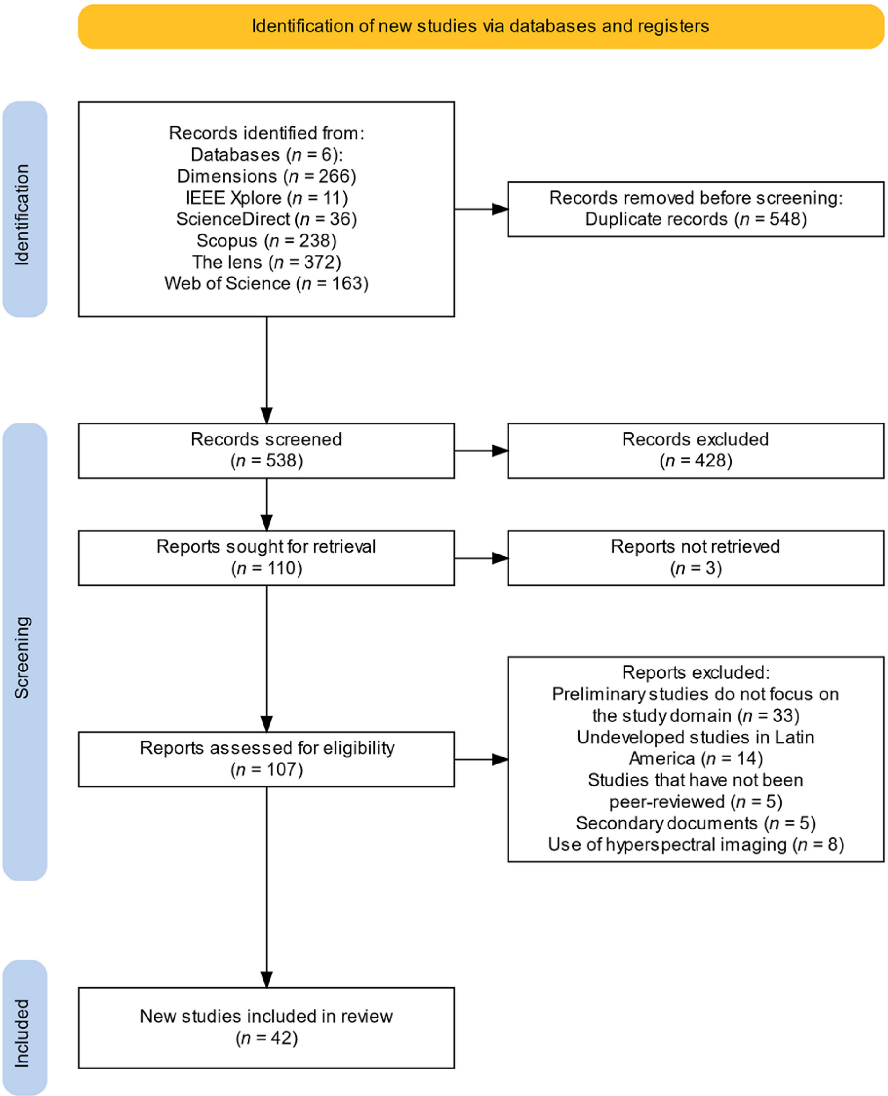

FIGURE 3 | Flowchart of the methodological steps according to the PRISMA methodology. [Colour figure can be viewed at wileyonlinelibrary.com]

indices derived from multispectral image analysis have been widely applied in various studies, from evaluating plant health status (Solis et al. 2021) to detecting pests and diseases (Cortez et al. 2020). By capturing multispectral images within a wavelength spectrum ranging from 365 to 970 nm, researchers have been able to explore design and apply different spectral indices.

In the Latin American region, it was observed that the Normalized Difference Vegetation Index (NDVI) is the most used spectral index in coffee production in Latin America, with 23.2% of use. It is followed by the Green Normalized Difference Vegetation Index (GNDVI), with 11.3%, the Normalized difference red edge index (NDRE), with 6.9%, and the simple ratio (RS), with 4.9%. These represent the spectral indices most frequently applied in coffee production in the Latin American region (Figure 5). In this sense, the review revealed a diverse range of spectral indices, indicating their potential within this domain, both on a Latin American and global scale. More than 45 unique and applicable indices were identified, demonstrating various options. These indices are used in various domains and throughout different stages of the coffee production process, from the initial planting phase to pest and disease detection, indicating multispectral imagery's versatility and broad applicability in agricultural practices.

One of the most versatile and widely used indices is the NDVI, which has proven helpful in estimating key biophysical parameters in coffee, such as biomass (Anfruns Espuña 2023), productivity, chlorophyll content, leaf area (dos Santos, Ferraz, de Carvalho, et al. 2022), and crop yield (de Souza Assis, Martins, and Orlando 2023). In addition, NDVI has been used in the early detection of pest and disease infections, which contributes to the integrated management of adversities in plantations.

The Soil-Adjusted Vegetation Index (SAVI) and the GNDVI are other commonly used indices in coffee research in Latin America. The SAVI adjusts calculations to minimize soil effects, particularly useful in early growth stages or areas with sparse vegetation cover (Zanella et al. 2024). On the other hand, the GNDVI focuses on the spectral response of vegetation in the green band, which makes it useful for estimating specific

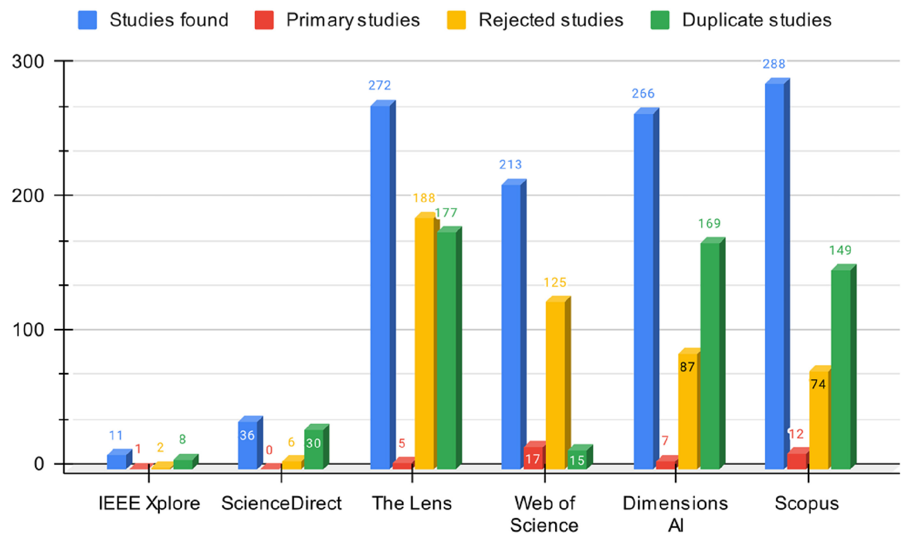

FIGURE 4 | Classifying contributions from scientific databases. [Colour figure can be viewed at wileyonlinelibrary.com]

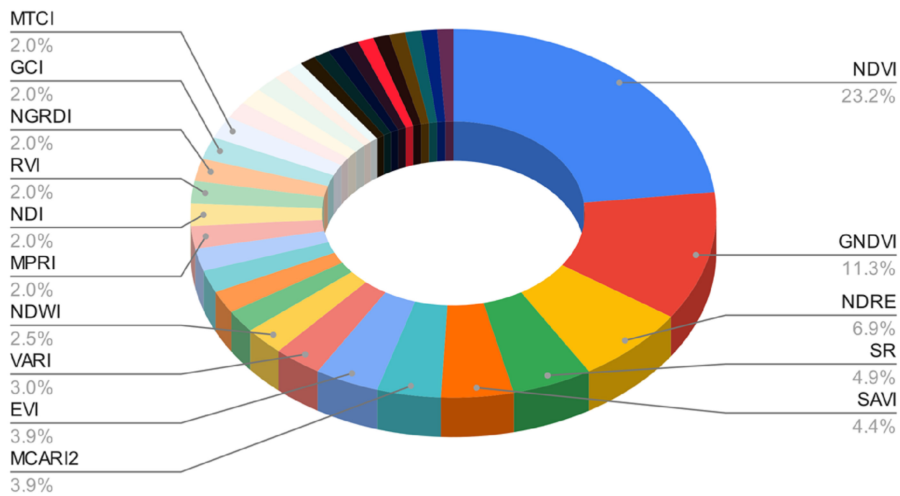

FIGURE 5 | Spectral indices are most used in coffee production in Latin America. [Colour figure can be viewed at wileyonlinelibrary.com]

biophysical parameters of coffee plants (Marin et al. 2023). Along these lines, the Modified Chlorophyll Absorption in Reflectance Index 1 (MCARI1) (Bolaños, Corrales, and Campo 2023) and the Modified Triangular Vegetation Index 1 (MTVI1) (Marin et al. 2019) have also been employed, which are specialized spectral indices that improve the detection of chlorophyll, which is an essential pigment for photosynthesis and, therefore, closely related to the health and yield of Latin American coffee plants.

In addition, indices such as the Normalized Difference Red Edge Index (NDRE), Water Stress Index (WSI), Photochemical Reflection Index (PRI), and Structure-Sensitive Pigment Index (SIPI) have been used to evaluate specific aspects of plant physiology, such as chlorophyll content, water stress, and the presence of photosynthetic pigments (Marin et al. 2022).

One element that attracts attention is the use of spectral indexes designed explicitly for coffee, such as the Coffee Ripeness Index (CRI) and Coffee-Leaf-Miner Index (CLMI), which have been used to estimate the degree of maturity of fruits and the early detection of pest infestations in crops, which is essential for determining the optimal harvest time and maximizing yields, thus contributing to the integrated management of pests and diseases in coffee plantations (Rosas et al. 2022; Vilela et al. 2023).

In addition to the spectral indices, others, such as the modified simple ratio (MSR) and the Modified Photochemical Reflectance Index (MPRI), have been used to estimate frost damage and assess the impact of increased atmospheric CO_2 concentration, respectively (Marin et al. 2021). These indices, remote sensing techniques, and multispectral image analysis establish a detailed picture of the state of coffee plantations, allowing accurate and timely interventions to improve productivity and crop sustainability.

Finally, spectral indices can be cataloged as essential tools in agricultural coffee research in the Latin American region. They provide objective and quantifiable data to evaluate plant health, productivity, and the detection of stress factors.

Q2. *What Kind of Physiological Parameters Are Inferred From Applying Multispectral Imaging in the Coffee Production Process in Latin America?*

Multispectral imaging, particularly spectral indices, has established itself as an instrumental method in the physiological evaluation of coffee crops. It allows the estimation of numerous significant parameters that yield crucial data on plant health, growth, and productivity.

A key parameter multispectral imaging assesses is chlorophyll content, studied in 28% of the research (Figure 6), both at individual leaves and the entire canopy level. Chlorophyll, a vital pigment for photosynthesis, directly indicates overall plant vigor and health. In addition, estimating other photosynthetic pigments, such as carotenoids, provides information on photosynthetic activity. Vegetation indexes such as NDVI assess crop biomass and vigor, while LAI provides vegetation density and extent data.

Multispectral images have also been used to evaluate the nutritional status of coffee plants; by analyzing different spectral signatures, it is possible to detect deficiencies or surpluses of essential nutrients (Marin et al. 2019), such as nitrogen (Rosas et al. 2022), phosphorus, potassium, magnesium (Zanella et al. 2024), and manganese, among others. This allows for optimizing fertilization practices and ensuring an adequate supply of nutrients to the plant. Thus, early detection of nutrient deficiencies facilitates precise interventions to maintain plant health (Vassallo-Barco et al. 2017). It is important to note that a significant part of the studies on nutrient deficiencies focus on nitrogen, given its essential role in plant growth and its substantial impact on coffee quality and yield.

Multispectral imaging is also helpful for detecting water stress in coffee plants (Anfruns Espuña 2023). Early indicators of water stress can be detected using specific spectral bands, allowing timely intervention that supports efficient irrigation management and water conservation in Latin American coffee crops (Castro 2019). Likewise, senescence (da Soares et al. 2022) and defoliation (Cortez et al. 2020) are additional physiological parameters evaluated through spectral indices, which indicate environmental stress or phenological stages. Likewise, photosynthetic activity, although more complex to estimate, has also been explored to better understand the plant's efficiency in converting light into energy (Thao et al. 2022).

Ultimately, the ability to estimate these physiological parameters noninvasively and on a large scale provides farmers with a valuable tool to make informed decisions and improve the management of their Latin American coffee crops. The scientific body of knowledge in this domain is progressing toward a complete understanding of the factors that influence the health and productivity of Latin American coffee plantations, positioning them as tools to improve the sustainability and quality of the final product.

Q3. *How Is the Data Obtained From Spectral Indices Through Images Used in the Coffee Production Process in Latin America?*

The acquisition and subsequent analysis of multispectral images have emerged as essential components in scientific research and agronomic management of coffee cultivation, providing a broad spectrum of data that facilitates the resolution of various problems and the improvement of coffee production methodologies (Solis et al. 2021). An important application of data derived from multispectral images is the precise differentiation between Arabica and Robusta, the two predominant coffee varieties grown in the Latin American region (Mihailova et al. 2022). In addition, these data are used to determine the degree of adulteration in blends of these varieties, thus guaranteeing the authenticity and quality of the final product and facilitating the production of differentiated, high-value products (Marin et al. 2021). For this purpose, AI is used, and supervised classification models are built using machine learning algorithms such as Support Vector Machine (SVM), Random Forest (RF), XGBoost, and CatBoost (Arteaga-López et al. 2022) (Marin et al. 2023).

Another outstanding use of these data is evaluating the quality of green coffee beans. By using multispectral reflectance and fluorescence, it is possible to classify beans according to their

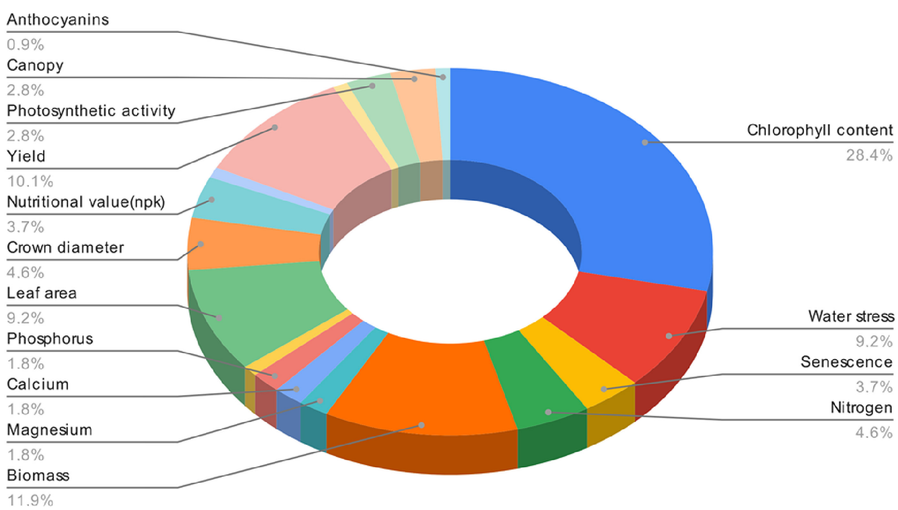

FIGURE 6 | Physiological parameters are estimated by the application of multispectral imaging in coffee crops. [Colour figure can be viewed at wileyonlinelibrary.com]

quality, distinguishing between "special" and "traditional" classifications (Gomes et al. 2022). This information has added value for producers and consumers, allowing them to make informed decisions about the product and sell it at better prices in international markets (Traore, Wilson, and Fields 2018).

Multispectral imagery is employed for the monitoring and management of Latin American coffee crops to identify areas impacted by frost (Marin et al. 2022), nutritional deficiencies, biotic stress (diseases, pests), and abiotic stress (soil, nutrients) (Esgario, Krohling, and Ventura 2020). This technology supports decision-making for management practices, including pruning (Marin et al. 2021), fertilization, and pest and disease control (Rezende et al. 2023), including coffee rust (*Hemileia vastatrix*) and coffee leaf miner (*Leucoptera caffeina*) (Vilela et al. 2023). In addition, these images facilitate continuous monitoring of the health and growth of coffee plants and the detection of crop failure (Ferraz et al. 2020). They are also utilized for phenological monitoring and assessing plant vigor, aiding in understanding growth dynamics and the influence of environmental and agronomic factors.

According to existing literature, another crucial aspect is the prediction of coffee yield on a regional scale through the development of statistical regression models (Bernardes et al. 2012) and the incorporation of machine learning techniques. In this regard, spectral data correlate with field data to estimate expected yield (de Souza Assis, Martins, and Orlando 2023), allowing for improved production planning and management of market needs. In addition, spectral indices are used to map the spatial variability of several key biophysical and agronomic parameters, which contribute to the zoning of plantations and the differentiated application of inputs, fertilizers, and irrigation according to the specific needs of each area (Anfruns Espuña 2023).

Considering the above, it is possible to indicate that the information derived from multispectral images applied to coffee cultivation is used integrally in various areas of the coffee production chain produced in Latin America, ranging from the classification of varieties to the monitoring of phytosanitary status, the evaluation of biophysical and agronomic parameters, the estimation of yields and the zoning of plantations. This information allows the management and sustainability of this crop to be optimized, contributing to informed decision-making and the implementation of more precise and efficient agricultural practices.

Q4. *What Types of Diseases, Pests, or Unfavorable Conditions Are Identified in Latin American Coffee Plantations Using Multispectral Images?*

In the specific context of Latin American coffee plantations, multispectral images have revealed the presence of diseases, pests, and adverse conditions that impact plant health and productivity (Mihailova et al. 2022). In this sense, it can be indicated that a large part of the studies (approximately 60%) did not indicate or study any pest or unfavorable condition, so it is a topic within the coffee production chain that perhaps needs to be worked on to a greater extent by the research community.

Regarding the diseases and adverse conditions found in the studies (Figure 7), it can be indicated that Coffee plant rust caused by the fungus *Hemileia vastatrix* (Cortez et al. 2020) is the most studied with approximately 43% of the studies, followed by leaf miner (*Leucoptera coffeella*) (dos Santos, Ferraz, Marin, et al. 2022) with approximately 30%. In addition, Cercosporiosis (*Cercospora coffeicola*) (Vilela et al. 2023) has also been studied to a lesser extent, with 7.7% of the studies. This speaks of the importance that the research community is giving to these pests and is by what has happened in recent times, where these types of diseases have afflicted the production of Latin American coffee (Koutouleas, Collinge, and Boa 2024), so the research community must continue to contribute to the domain from these computer vision techniques to mitigate the damage caused by these pests.

Specifically, one of the most relevant diseases detected by multispectral imaging is coffee plant rust, caused by the fungus *Hemileia vastatrix*. This fungal disease causes significant defoliation and can lead to considerable losses in production, especially in years of high productivity (Naoya Katsuhama, Imai, and Takahashi 2018). In this regard, several studies have demonstrated the ability of multispectral images to identify the presence of this disease in coffee plantations (Cortez et al. 2020; Ghazali et al. 2020; da Soares et al. 2022). In addition to rust, multispectral images have made it possible to detect the infestation *of Leucoptera coffeella*, an insect pest that feeds on leaf tissue, causing defoliation and reducing the photosynthetic capacity of the plants (Marin et al. 2019). Another disease mentioned is cercosporiosis, caused by the fungus *Cercospora coffeicola*, which can also be identified using this technique (Ghazali et al. 2020).

Apart from specific diseases and pests, multispectral imaging has helped to assess adverse conditions that affect the development and yield of coffee plants. These include water stress (Chemura, Mutanga, and Dube 2017a), nutritional deficiencies (especially nitrogen), and the presence of nematodes in the soil (de Abreu Júnior et al. 2022), which can infect plant roots and compromise plant growth. Likewise, these images have proven effective in detecting damage caused by abiotic factors, such as frost (Marin et al. 2021), manifesting in coffee leaves' senescence and necrosis. This information is crucial for implementing precise and timely agronomic interventions to mitigate the adverse effects on coffee production.

The empirical evidence suggests that multispectral imaging is a valuable tool for monitoring the health of coffee plantations. It leads to early detection of these adverse factors and enables a rapid and accurate response, which helps to protect the coffee industry and ensure its long-term sustainability.

Q5. *What Are the Advantages and Disadvantages of Using Spectral Indices Compared to Other Methods of Sanitary Evaluation in the Coffee Production Process in Latin America?*

The evaluation of the health status of coffee plantations in Latin America is a critical factor in maintaining optimal and sustainable yields of this type of crop. In this regard, spectral indices have been identified as a potential tool, providing substantial benefits over alternative assessment techniques. A key advantage of spectral indices is their ability to detect pests (Bonnaire Rivera, Montoya Bonilla, and Obando-Vidal 2021), diseases, and nutritional deficiencies early, improving

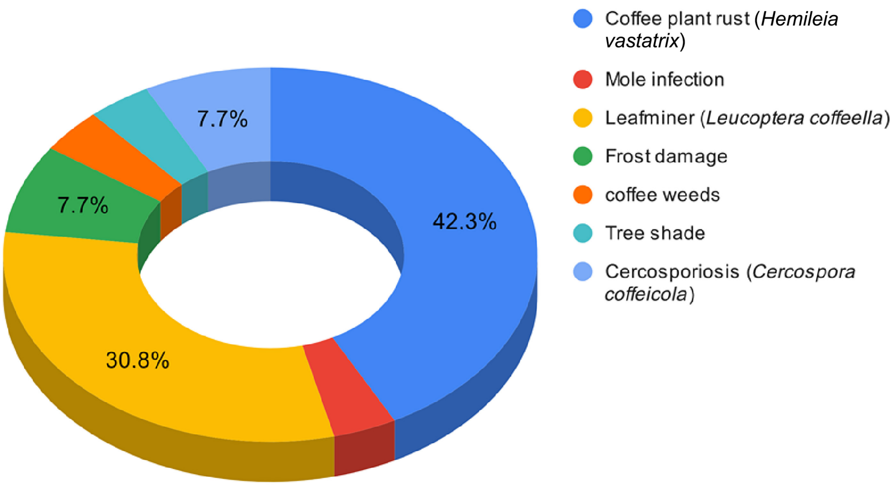

FIGURE 7 | Diseases and adverse conditions estimated by multispectral imaging in Latin American coffee plantations. [Colour figure can be viewed at wileyonlinelibrary.com]

phytosanitary control and management (Marin et al. 2019). By evaluating the reflectance of light at various wavelengths, these indices can identify signs of stress in plants before their visual manifestation, allowing for rapid intervention (Solis et al. 2021).

Another significant advantage of spectral indices is their noninvasive nature, which respects the integrity of the plant (Barata et al. 2023). In addition, they are often more cost-effective and faster to implement than conventional methods, such as intensive sampling or laboratory analysis (Anfruns Espuña 2023). This economic and time efficiency improves their accessibility for farmers, mainly when technologies such as standard cameras or unmanned aerial vehicles (UAVs) are employed (Bonnaire Rivera, Montoya Bonilla, and Obando-Vidal 2021).

Spectral indices are also notable for their ability to monitor large-scale areas, enabling remote and continuous assessment of extensive crop regions, providing a comprehensive and detailed perspective of planting conditions, and aiding decision-making and crop management (de Souza Assis, Martins, and Orlando 2023). Furthermore, by providing spatially explicit, high-resolution data, these indices facilitate a more accurate analysis of the distribution of crop health problems (Jorge Luis Aroca Trujillo 2023).

However, spectral indices also face challenges in their implementation that deserve attention at the time of their application or to increase their utilization rate. In this regard, the quality of the images used to calculate the indices may affect their accuracy and efficiency, as factors such as resolution, cloudiness, and illumination influence (Arteaga-López et al. 2022; Revelo Luna et al. 2020). In addition, spectral indices may require validation with complementary field data and analysis to accurately interpret the results, which can add complexity and time to the process (Anfruns Espuña 2023). Specific spectral indices may also show decreased sensitivity under specific circumstances, such as the presence of mature plants (Barata et al. 2023) or saturation of bands linked to chlorophyll absorption (Chemura, Mutanga, and Dube 2017b), which could hinder their ability to identify specific crop health problems. Finally, the image processing required to calculate spectral indices can be complex and require specialized technical expertise, which could limit their adoption by some farmers (da Soares et al. 2022). These considerations should be carefully evaluated when integrating this technology into coffee plantation management, and its application can be complemented with other health assessment techniques to achieve a more complete and accurate crop health assessment.

5 | Discussion

This systematic mapping, guided by the PRISMA protocol (Figure 3) and Petersen's methodology (Figure 1), has significant trends and opportunities in applying multispectral imagery and vegetation index to coffee production in Latin America. The analysis, based on 42 primary studies identified through a systematic search (Table 2), inclusion and exclusion criteria (Table 3), and six databases (Figure 4), highlights the dominance of the NDVI in the studies (Figure 5) highlights its versatility and reliability in assessing biophysical parameters, aligning with other research on agricultural remote sensing, where NDVI has proven valuable in various crops (Fletcher and others 2019). However, the emergence of specialized indices such as the CRI and CLMI Index points to a growing trend toward crop-specific spectral tools, which may offer increased accuracy in coffee-specific applications, as reported in the scientific corpus (Nogueira Martins et al. 2021). In this context, there is empirical evidence of successful cases in Latin America of multispectral imagery in support of coffee production (de Abreu Júnior et al. 2022; Silva, Varela, and Lezama 2021), underlining the importance of this technological approach and its future potential in the region.

The concentration of research efforts in specific Latin American countries, particularly Brazil and Colombia, reflects their crucial role in world coffee production but also reveals a potential gap in the literature. As mentioned in Harvey et al. (2021), this geographic disparity in research presents an opportunity to expand the application of multispectral imaging techniques to other coffee-producing regions in Latin America.

The research questions outlined in Table 1 guided the study on the types of physiological parameters inferred from multispectral imagery; their ability to estimate critical physiological parameters noninvasively (Figure 6) was a significant advance in crop monitoring. This approach provides valuable data on plant health and productivity and aligns sustainable agriculture practices by minimizing physical disturbances to the crop (Li et al. 2022). The ability to detect water stress, nutrient deficiencies, and early signs of pest infestation through spectral signatures offers a proactive approach to crop management, potentially reducing the need for broad-spectrum interventions and supporting more targeted and efficient use of resources (Ahmad, Alvino, and Marino 2021; Safdar et al. 2023).

The application of multispectral imaging in detecting specific diseases and pests, particularly *Hemileia vastatrix* and coffee leaf miner (Figure 7), demonstrates its potential for early intervention in pest and disease management (De Silva and Brown 2023). However, the relatively low percentage of studies focused on specific pests or diseases (approximately 40%) suggests an opportunity for more targeted research in this domain. Given the significant economic impact of these biotic stresses on coffee production, further research on multispectral imaging for early detection and monitoring of a broader range of pests and diseases could contribute significantly to integrated pest management strategies in coffee cultivation, as mentioned in the literature on domain (Orlando et al. 2024; Xiao et al. 2022).

Finally, this research (Figure 2) highlights that multispectral imagery and vegetation index substantially benefit coffee production in Latin America. Although challenges remain, these technologies' potential to improve the accuracy and efficiency of agricultural practices is undeniable. Continued research and technological advances will be essential to harness the full potential of multispectral imagery for sustainable coffee production.

6 | Threats to Validity

In conducting this systematic mapping of the literature on the application of spectral imagery and vegetation indices in coffee production in Latin America, several potential threats to validity were identified and addressed. These threats include the following:

- *Search string limitations*: Despite being detailed, the search string may not have captured all relevant studies due to variations in terminology or indexing in different databases. To mitigate this, a wide range of synonyms and related terms were used in the search string.
- *Database selection*: The choice of databases may have excluded relevant studies from other sources. To mitigate this, a manual search was performed for relevant articles that may have escaped the search string.
- *Geographic limitation*: The focus on Latin America, although intentional, limits the generalizability of the findings to other coffee-producing regions. Future research could expand the geographic scope for a more complete global perspective.
- *Temporal bias*: The review covered all available studies up to May 2024, which may need to capture more recent developments in the field. Periodic updates of the review would help mitigate this threat.
- *Technological bias*: Rapid advances in multispectral imaging technology and data analysis techniques could make some study's findings less studied or outdated over time. To mitigate this, the dynamic nature of the field is recognized, and the need for continued updates and future research is emphasized.

7 | Conclusions

This study systematically maps the literature on applying spectral indices in coffee production in Latin America, adhering to the PRISMA protocol and Petersen guidelines. Significant trends are discovered by analyzing the implementation of multispectral imaging in coffee cultivation in this region, and areas for future research are identified. Based on 42 primary studies, the analysis highlighted NDVI's dominance as the most widely used spectral index, reflecting its versatility in estimating crucial biophysical parameters such as biomass, chlorophyll content, and yield. Other indices such as GNDVI, NDRE, SAVI, and CRI also emerged as valuable tools for assessing coffee health and development. Specialized indices such as CRI and CLMI highlight the potential for developing crop-specific spectral tools.

A notable concentration of research efforts in certain Latin American countries, particularly Brazil and Colombia, suggests an opportunity to expand research and the application of multispectral imaging techniques in other coffee-producing regions of Latin America. This presents a valuable opportunity to further explore this technology's versatility in diverse agroecological contexts and adapt its application to specific regional challenges.

In this line, multispectral imaging has proven effective in estimating key physiological parameters such as chlorophyll content, biomass, leaf area index, and water stress. This noninvasive approach provides valuable information on plant health and productivity, allowing more informed decisions in coffee cultivation. It was also found that integrating multispectral imaging with machine learning and AI techniques is an emerging trend, promising to improve data interpretation accuracy and efficiency for various coffee production applications. Further integration with AI and Internet of Things technologies is anticipated, enabling real-time monitoring and automating decision-making processes. This will likely lead to more sustainable and efficient coffee production systems.

Despite multispectral imaging's many advantages, such as its noninvasiveness, cost-effectiveness, and ability to rapidly cover large areas, some challenges remain. These include the need for specialized expertise in image processing and interpretation and possible limitations in image quality due to environmental factors. Therefore, future research should address these issues and develop more robust and user-friendly systems for widespread adoption. In addition, integrating multispectral data with other sources, such as soil sensors and meteorological data, could contribute to a more holistic view of coffee plant health and environmental conditions.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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