Colegio de Postgraduados

Nutritional Diagnosis in Oil Palm Using UAV-Based Multispectral Imagery: A Global Bibliometric Analysis, 2005-2024

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ABSTRACT

This study examines trends in research productivity, thematic evolution, and knowledge gaps regarding the use of unmanned aerial vehicles (UAVs) equipped with multispectral sensors for nutrient diagnosis in oil palm plantations. A bibliometric analysis was conducted on publications indexed in Web of Science and Scopus over the 2005-2024 period, following four phases: 1) a qualitative exploratory review of 50 scientific articles to identify search terms; 2) a comprehensive systematic search using 83 search equations, without restrictions on language, document type, or research area; 3) temporal delimitation through frequency analysis; and 4) cross-validation through thematic relevance mapping. The extracted data included title, authors, keywords, abstract, publication year, citations, and country.

The bibliometric analysis reveals a substantial knowledge gap in the application of multispectral UAV technology for estimating nutrient concentrations in oil palm. Despite the exponential growth of UAV research during 2017-2024 and plant nutrition studies during 2005-2024, the intersection of these fields in oil palm remains markedly underdeveloped, with only five publications identified. Research is concentrated in Malaysia (30%), consistent with its status as the world's leading producer. This gap constitutes both a challenge and a promising opportunity for future research, particularly in the development of standardized protocols for non-destructive nutrient diagnosis that could help address production stagnation in plantations.

Keywords: bibliometric, UAV, Oil palm, nutrient.

INTRODUCTION

Agricultural crop productivity is multifactorial, with nutritional status representing one of the most decisive factors in the expression of the genetic potential of crops (Marschner and Marschner, 2012). This factor accounts for up to 60% of yield variation when elements such as water and solar radiation are not limiting (Fageria *et al.*, 2011). This premise is

grounded in the Law of the Minimum established by Justus von Liebig in 1840, which states that plant growth and development are constrained by the scarcest nutrient, even when all other nutrients are present at optimal levels (Van Der Ploeg *et al.*, 1999). Therefore, timely nutritional diagnosis constitutes a strategic component of agronomic management, particularly in long-cycle perennial crops, where deficiencies may affect yield up to 24 months later (Rhebergen *et al.*, 2019).

Historically, the diagnosis of crop nutritional status has relied on destructive plant tissue sampling for laboratory analysis. Because this approach represents only a minute fraction of the total biomass, it introduces estimation errors that become magnified in large-scale plantations. Consequently, fertilizers are often applied uniformly across spatially variable fields, resulting simultaneously in overfertilized and nutrient-deficient zones, with adverse economic and environmental consequences (Robertson *et al.*, 2013).

In the specific case of oil palm, these limitations of conventional diagnosis partially explain the lower productive efficiency observed in cultivated plantations. Although this crop can attain yields of 10 tons of crude palm oil per hectare per year under optimal conditions (Barcelos *et al.*, 2015; Corley and Tinker, 2016), the global average remains stagnant at 2.8 t ha^{-1} $year^{-1}$. This yield gap has driven global expansion of cultivated area at an average rate of one million hectares per year (Food and Agriculture Organization of the United Nations [FAO], 2024).

In response to the inherent limitations of destructive leaf sampling, remote sensing using unmanned aerial vehicles (UAVs) equipped with multispectral sensors has emerged as a technological alternative for non-destructive nutritional diagnosis. UAVs provide spatial information at centimetric resolution and temporal flexibility, attributes that are particularly relevant in tropical agricultural systems, where plantation scale, soil heterogeneity, and climatic conditions hinder conventional monitoring based on point sampling (Matese *et al.*, 2015).

In tropical contexts, this capability becomes especially important because perennial crops such as oil palm exhibit dense, stratified canopies, continuous phenological cycles, and nutritional variability that demand diagnostic tools with high spatial resolution. Likewise, these systems require temporal frequencies capable of adapting to the narrow operational windows imposed by persistent cloud cover.

Recent scientific literature documents successful applications of multispectral UAVs for nutritional diagnosis in diverse crops, including nitrogen in rice (*Oryza sativa* L.) (Yang *et al.*, 2025), phosphorus and potassium in apple (*Malus domestica* Borkh.) (Sun *et al.*, 2023), and multiple nutrients in maize (*Zea mays* L.) (Cheng *et al.*, 2024; Han *et al.*, 2022). Nevertheless, most of these advances have been developed in temperate agroecosystems with low-stature annual crops, which limits their direct extrapolation to tropical perennial plantations.

Despite the exponential growth of this field, no comprehensive bibliometric analysis has yet systematically synthesized trends in scientific productivity and the critical knowledge gaps that constrain technological transfer toward large-scale commercial adoption in the tropics. Previous reviews, such as those by Mulla (2013) and Khanal *et al.* (2020), focused on satellite remote sensing and general UAV applications in agriculture; however, none has consolidated, through bibliometric analysis, the specific body of knowledge concerning nutritional diagnosis with multispectral sensors in tropical perennial crops. This lack of synthesis is further exacerbated by the difficulty of determining precisely when UAVs began to be applied to agricultural nutritional assessment. Such uncertainty complicates the temporal delimitation of a field that has evolved in a fragmented manner across disciplines such as tropical agronomy, remote sensing, and data science.

Given the need to consolidate the dispersed scientific knowledge on the use of UAVs equipped with multispectral sensors for agricultural nutritional diagnosis, and considering the absence of a precise record of their origin in agriculture, particularly in oil palm, it is methodologically necessary to adopt a longitudinal approach. This perspective will make it possible to capture not only the emergence of these technologies, but also the evolution of the nutritional monitoring methods that preceded them. Within this framework, the following research question arises: What are the trends in scientific productivity, thematic evolution, consolidated methodological protocols, and critical knowledge gaps in the use of UAVs equipped with multispectral sensors for nutritional diagnosis in agricultural crops? This bibliometric analysis will enable the systematic identification of the knowledge gaps that should be addressed through future research.

MATERIALS AND METHODS

An exploratory-descriptive bibliometric design was employed to examine the scientific literature using the Web of Science (WoS) and Scopus databases, both widely recognized for their exploratory capacity and rigorous scientific indexing (Singh *et al.*, 2021). The study was structured into five phases.

In phase one, the search terms were identified through an exploratory analysis of 50 scientific articles related to nutritional diagnosis in oil palm, agricultural remote sensing, and UAV applications. From each article, author keywords and frequently occurring terms in titles and abstracts were extracted. These terms were subsequently grouped into categories. In phase two, a comprehensive stepwise search strategy was designed at three levels: (i) simple searches by individual term, (ii) binary combinations across categories, and (iii) the complete integration of the three groups. This combinatorial approach generated 83 search equations (11 simple, 36 binary, and 36 triple), adapted to the syntax of each database. No restrictions were applied regarding language, document type, or subject area in order to maximize comprehensiveness. The following data were extracted from each record: title, authors, author keywords, full abstract, publication year, citation count, and country. In phase three, temporal distribution was analyzed through annual frequency series and interannual growth rates, with the aim of identifying inflection points associated with technological milestones and defining the optimal temporal range for detailed analysis. The selection criterion was established as the interval encompassing at least 75% of the accumulated productivity. Likewise, citation count was used as an impact indicator to identify seminal publications. In phase four, thematic filtering was applied to the publications included within the previously delimited optimal temporal range, based on three simultaneous inclusion criteria: (i) the study specifically addressed oil palm, (ii) its primary focus was nutritional diagnosis or deficiency identification, and (iii) it employed multispectral imagery acquired through UAVs. Similarly, studies on other crops without direct comparison to oil palm, investigations lacking a nutritional component, studies based exclusively on satellite imagery, duplicate records, and documents without an available abstract were excluded. In phase five, descriptive analysis and keyword co-occurrence network analysis were conducted using VOSviewer v. 1.6.20 (van Eck & Waltman, 2010), establishing a minimum threshold of two occurrences.

RESULTS AND DISCUSSION

Critical Elements of the Research

The analysis made it possible to identify 11 terms associated with the conceptual axes of the study. These terms were classified into three thematic categories, namely: A) target crop, B) nutritional diagnosis, and C) UAV-based remote sensing (Table 1). These terms constituted the foundation of the investigation and will hereafter be referred to as critical elements.

Thematic Context

The comparative analysis between the WoS and Scopus databases revealed substantial differences in the volume of indexed publications. WoS registered a total of 979,773 records, exceeding Scopus (880,641 articles) by 11%. Nevertheless, both databases exhibited exponential growth in the number of publications over the analyzed period. The distribution across thematic categories revealed a marked asymmetry in scientific output (Table 1). Category B (nutritional aspects) accounted for 78% of the total publications, with 766,634 articles in Scopus and 589,702 in WoS. In contrast, Category A (crop) represented less than 1%. This seemingly anomalous disproportion is interpreted as a consequence of the broad semantic scope of the term “nutrient.”

Likewise, within each category, a concentration around specific terms was observed, which functioned as thematic cores. Term A1 (oil palm) accounted for 84% of the publications within Category A, whereas B2 (nutrient) represented virtually the entirety of Category B. In turn, within Category C, the term UAV accounted for 37% of the publications in that category (Table 1).

The combination of two categories makes it possible to identify consolidated lines of research. The A1-B2 intersection yielded 904 publications in Scopus and 970 in WoS, representing the most robust research line focused on crop nutrition. The second significant intersection occurred between B2-C1, with 383 and 321 publications, respectively,

Table 1. Search terms grouped into three thematic categories.

C –UAV-Based Remote Sensing	B-Nutritional Diagnosis	A-Crop	
UAV	Nutrient	Oil palm	1
Drone	Nutrient	African oil palm	2
Dron		*Elaeis guineensis*	3
RPA			4
Unnamed vehicle aerial			5
RPAS			6

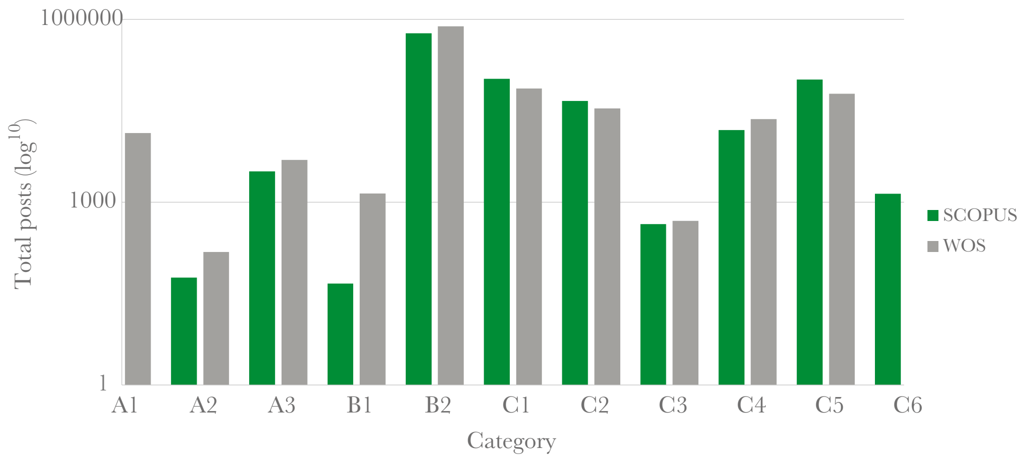

Figure 1. Number of publications of the critical elements on a logarithmic scale. Category B stands out prominently in both databases.

indicating steady growth in this line of research. In turn, the B2-C5 combination also showed notable relevance, with 376 articles in Scopus and 259 in WoS, suggesting that the term UAV appears more frequently in the literature than its full designation (Figure 2).

The intersection of the three categories (Figure 3) reveals an extremely limited, yet meaningful, landscape. The principal line, A1-B2-C1, accounts for five articles in total, whereas A1-B2-C5 yielded only three articles, and the A3-B2-C5 intersection resulted in merely three publications (Figure 3). This extreme scarcity of studies simultaneously integrating crop-related, nutritional, and technological dimensions represents less than 0.001% of the total volume analyzed.

Commercial Development of oil palm and scientific research

The establishment of oil palm as a commercial plantation crop can be situated within the period from 1907 to 1950. During this interval, oil palm evolved from a system of

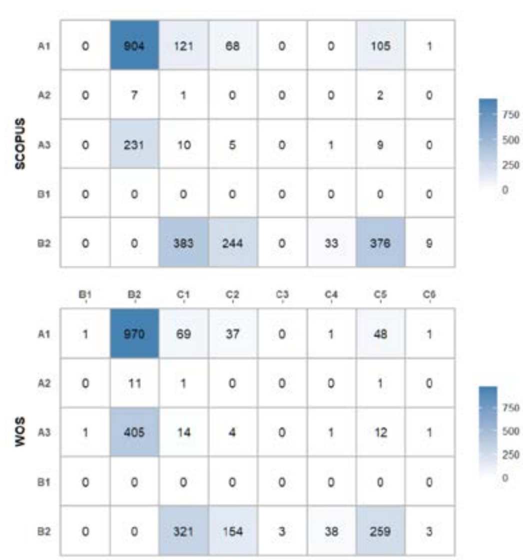

Figure 2. Diagram of the binary combination of categories.

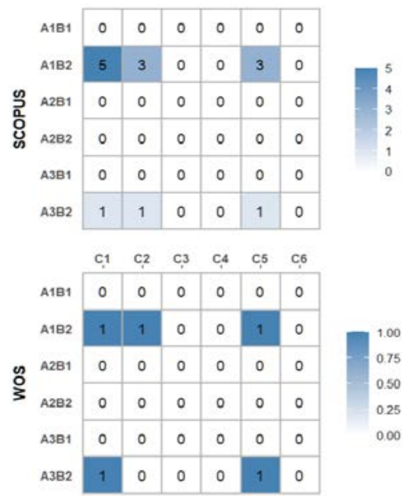

Figure 3. Diagram of the intersection of the three categories.

wild harvesting in Nigeria (1907) (Sarbah, 1909) to organized plantation systems, first in Indonesia and the Democratic Republic of the Congo (1911), followed by Malaysia in 1917 (Din, 2019). This expansion was substantial and became firmly consolidated during the 1940s, when Nigeria, Indonesia, the Democratic Republic of the Congo, and Malaysia led global production. However, intensification under monoculture created favorable conditions for the emergence of phytosanitary problems, as reflected in the entomological nature of the earliest scientific publications. Among these were the description of nematodes by Yampolsky (1924), the incidence of the fungus *Fusarium oxysporum* in African plantations (Wardlaw, 1946), the beetle *Cephalolia elaeidis* described by Maulik (1920), and the moth *Pimelephila ghesquierei* reported by Tams (1930). The predominance of pest-related studies indicates that biological challenges during the early decades of commercial cultivation largely determined the initial research priorities. Consequently, studies on plant nutrition gained relevance toward the end of the 1940s with the work of Chapman and Gray (1949). During this period, the development of the Beckman DU spectrophotometer by Arnold Beckman proved decisive for the systematic nutritional monitoring of commercial plantations, as it significantly reduced analysis time. Research was concentrated in three principal geographic centers —Malaysia, the United Kingdom, and the United States— which collectively produced 29 publications, a figure that contrasts sharply with the rapid pace of commercial plantation expansion.

Nevertheless, the most accelerated period of oil palm establishment occurred from 1950 onward, when the crop expanded to 43 territories, covering an estimated 3.4 million hectares worldwide (Food and Agriculture Organization of the United Nations [FAO], 2024), with Nigeria, Malaysia, the Democratic Republic of the Congo, and Guinea as the main producers. Once plantations were established, the field entered a transition toward a period of research maturity, evidenced by the diversity of topics aimed at intensifying production (Table 2). These included foundational studies on oil palm growth (Corley *et al.*, 1971), germination protocols (Rees, 1962), optimization of planting densities (Corley, 1973), pathological characterization of economically important species (Turner, 1965;

Sankaran, 1970), and analyses of fruit yield (Hardon *et al.*, 1969). Other studies addressed nutritional aspects (Munsell *et al.*, 1950) and the digestibility of palm oil for human consumption (Iwatsuru and Nakamura, 1950).

More specifically, research on crop nutrition increased substantially in two stages. In the 1950s, macronutrients were of primary importance, with particular emphasis on potassium. Subsequently, in the 1970s, attention shifted toward the identification of boron as a critical micronutrient. Scientific output was led by Malaysia, the Netherlands, Nigeria, the United Kingdom, the Congo, Scotland, and the United States.

The definitive consolidation of oil palm research took place between 1975 and 2000, with a total of 970 publications, averaging 39 articles per year. During this period, research emphasized the diverse applications of oil palm residues, including the use of natural fibers for composite materials (Sreekala *et al.*, 1997; Wollerdorfer and Bader, 1998), wood utilization (Zaini *et al.*, 1996), food applications and effects on human health (Torstensen *et al.*, 2000), as well as charcoal production from residues (Guo and Lua, 2000). In parallel, mathematical models were developed to describe growth (Goudriaan and Monteith, 1990) and pollination processes (Syed, 1979).

In contrast, research on nutrition declined during this period. The countries generating the highest scientific output were Malaysia, the United Kingdom, France, Nigeria, the United States, England, and Côte d'Ivoire. By that time, the estimated global oil palm area had reached 10.3 million hectares distributed across 44 territories, among which Malaysia, Nigeria, and Indonesia stood out prominently.

Finally, the most significant period recorded an average of 589 articles per year and accounted for more than 75% of total scientific output. This stage began specifically in 2005, showing a direct correlation between the number of articles and harvested area, which suggests that research output was driven by the expansion of cultivated land. The comparative analysis further showed that Scopus contained 7% more articles than WoS,

Table 2. Literature frequency by critical element, elements A1, B2, C1 represent the highest frequency.

	Rank		**A1**	**A2**	**A3**	**B1**	**B2**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**TOTAL**
SCOPUS	2000	2025	15.90	0.05	2.91	0.04	502.82	105.04	44.72	0.33	12.04	102.18	1.34	787.37
	1975	2000	0.75	0.00	0.25	0.00	79.28	0.42	0.75	0.10	2.89	0.32	0.04	84.80
	1950	1975	0.12	0.00	0.03	0.00	7.12	0.00	0.19	0.00	0.35	0.00	0.00	7.81
	1925	1950	0.02	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.44
	1900	1925	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.07
	Total		20 166			589 748		270 727						
	Rank		**A1**	**A2**	**A3**	**B1**	**B2**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**TOTAL**
WOS	2000	2025	12.46	0.15	4.16	1.37	63.60	73.21	33.31	0.31	17.18	60.14	1.18	267.07
	1975	2000	0.99	0.00	0.67	0.00	113.89	0.30	0.99	164.00	5.62	0.00	0.04	286.50
	1950	1975	0.10	0.00	0.10	0.00	13.90	0.00	0.16	0.00	0.36	0.00	0.00	14.62
	1925	1950	0.01	0.00	0.00	0.00	2.76	0.00	0.00	0.00	0.00	0.00	0.00	2.77
	1900	1925	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.14
	Total		18 663			768 016		193 094						

*Thousands of items. The descriptions are related to Table 1.

with exponential growth beginning in 2005. In contrast, the trend in WoS has declined over the last five years. This scientific productivity is concentrated primarily in Malaysia (30%), Indonesia (17%), and the United Kingdom (0.05%).

Convergence of the Temporal and Thematic Axes of Research

The temporal and thematic analysis makes it possible to establish a solid research axis defined as nutrient –oil palm– UAV, which emerges in response to the need for efficient nutritional monitoring of oil palm plantations. The term co-occurrence analysis identified the following thematic clusters: (i) oil properties and derivatives, (ii) biomass utilization, (iii) deforestation (Gibbs *et al.*, 2010), (iv) charcoal properties and applications (Wu *et al.*, 2009), and (v) biodiversity (Fitzherbert *et al.*, 2008; Koh and Wilcove, 2008).

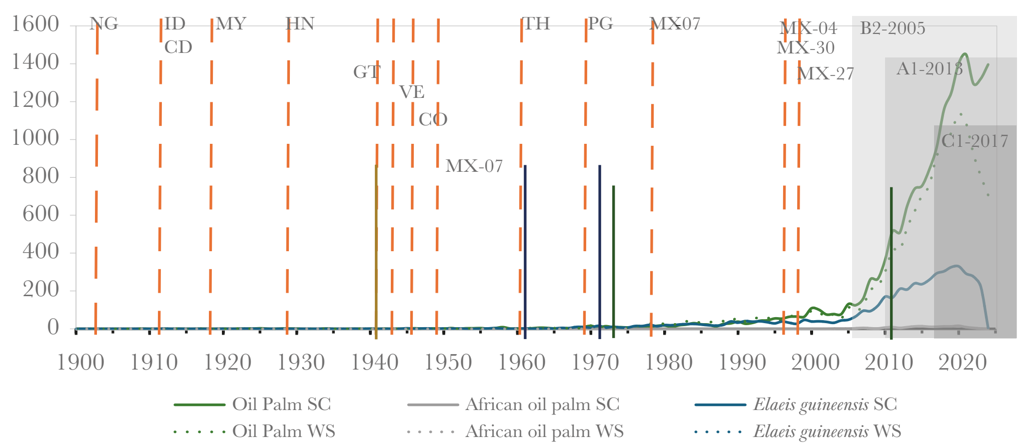

Figure 4. Frequency of publications per year (1900-2024) of critical research categories, along with geographical expansion of oil palm, the period of greatest publication of nutrient, oil palm and UAV.

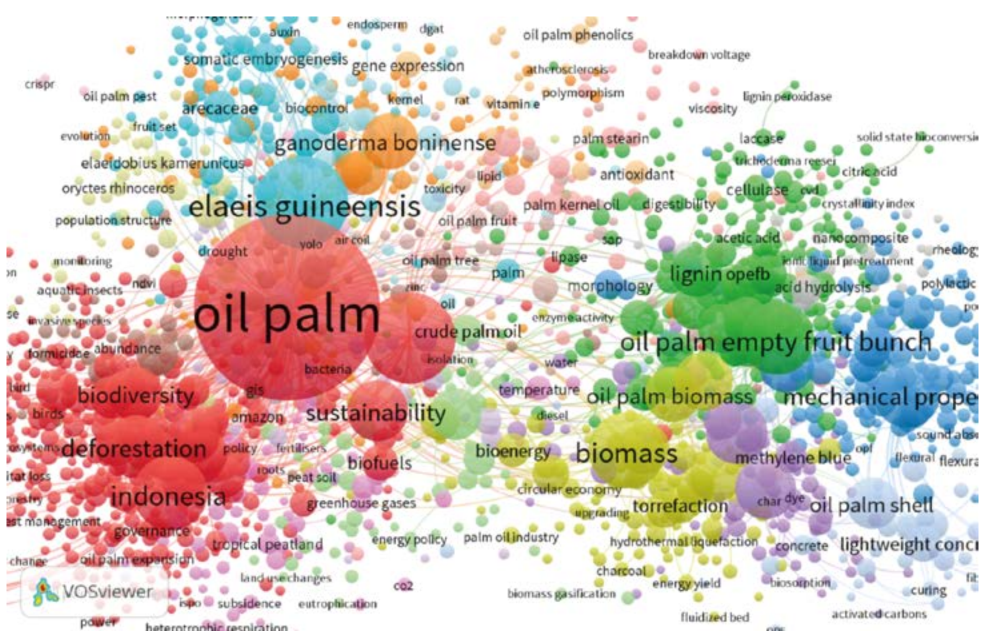

Figure 5. Thematic co-occurrence network for the 2005-2024 period.

The exhaustive search conducted across the two databases revealed significant disparities in the retrieval of specialized information, as the specific search equation UAV nutrient oil palm yielded only one article in WoS, compared with five documents in Scopus. This quantitative difference suggests variations in the indexing algorithms and thematic coverage of each platform, particularly in research integrating multiple technological disciplines, which is consistent with the findings of Mongeon and Paul-Hus (2016) regarding asymmetries in coverage across bibliographic databases. The five documents identified in Scopus comprise three scientific articles, one conference paper, and one conference review, suggesting that this research line remains in an emergent stage and is still undergoing methodological consolidation, where scientific output has not yet reached the critical mass characteristic of mature disciplines (Donthu *et al.*, 2021). Consequently, the simultaneous consultation of multiple databases constitutes an indispensable strategy to ensure the comprehensiveness of reviews in interdisciplinary fields with incipient scientific production (MacDonald *et al.*, 2024).

The results reveal high variability despite the use of spectral imagery acquired by remotely piloted aircraft systems (RPAS). This variability may be explained by the application of different data analysis techniques; moreover, it should be considered that this technology is relatively recent in comparison with agronomic concepts that have been established for more than a century. Uktoro *et al.* (2024), through image classification, obtained a very low coefficient of determination (R^2=0.413) for the estimation of nitrogen, phosphorus, and potassium. Santoro (2024) reported correlation coefficients of 0.81 for nitrogen and phosphorus, and 0.90 for potassium, magnesium, and calcium, using vegetation indices; however, boron estimation showed important limitations, with an R^2 of 0.26. Likewise, Amirruddin *et al.* (2022) achieved an R^2 of 0.77 for nitrogen estimation by implementing synthetic minority oversampling and machine learning.

CONCLUSION

Therefore, it is concluded that the technological convergence analyzed is currently in a transitional stage, moving from academic theory toward technical validation under field conditions. It is therefore imperative to promote research aimed at standardizing the use of multispectral sensors in perennial crops, thereby enabling the closure of the gap between the data acquisition capacity of UAVs and the precise physiological interpretation of the nutritional status of oil palm.

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