International Journal of Agriculture and Biosciences 2026 15(3): 1034-1043.
https://doi.org/10.47278/journal.ijab/2026.022

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Fertilization-Induced Changes in Leaf Nutrient Composition and Canopy Reflectance of *Gardenia jasminoides* in the Visible and Near-Infrared Spectrum

Wisam M. Obeidat [1,*], Yahia A. Othman[2] and Njood M. Al-Zaben[2]

[1]The University of Jordan, Department of Plant Protection, School of Agriculture, Amman 11942, Jordan
[2]The University of Jordan, Department of Horticulture and Crop Science, School of Agriculture, Amman, 11942, Jordan
*Corresponding author: wi.obeidat@ju.edu.jo

ABSTRACT

Advanced sensing technologies, particularly hyperspectral sensing, provide a powerful, non-destructive approach for monitoring plant physiological responses to nutrient status and environmental conditions. This study aimed to compare the effects of two fertilization application methods (foliar spraying and soil drenching) on leaf nutrient uptake (N, P, K, Ca, Mg, and Fe) in *Gardenia jasminoides* cv. 'Fortuniana', assess their impact on canopy spectral reflectance, and explore correlations between leaf nutrient concentrations and hyperspectral reflectance to identify potential remote sensing indicators of nutritional status. The experiment was conducted in the greenhouse using a randomized complete block design (RCBD) with four replications, with five pots per block over one year. Gardenia plants were fertilized using either foliar spraying or soil drenching, followed by leaf nutrient analysis and canopy-level reflectance measurements in the visible (400-700nm) and near-infrared (700-950nm) ranges. Soil drenching significantly increased leaf N, P, and Ca concentrations, while foliar spraying enhanced Mg and Fe under foliar treatment. Nutrient ratios also differed between treatments, reflecting distinct internal nutrient balances. Spectrally, foliar-sprayed plants exhibited higher reflectance in the visible region, while soil-drenched plants showed stronger reflectance in the near infrared reflectance (NIR) range. Key wavelength regions with strong normalized difference indices (NDI) correlation were identified for nutrient monitoring: 400-430, 580-640, and 700-720nm for foliar spray, and 700-950nm for soil drenching. These findings underscore the potential of hyperspectral sensing for non-invasive, multi-nutrient diagnostics and optimized fertilizer management in precision agriculture.

Keywords: Hyperspectral, Remote sensing, Reflectance, Mineral ratio, Vegetation index.

Article History
Article # 25-582
Received: 25-Sep-25
Revised: 02-Nov-25
Accepted: 25-Nov-25
Online First: 16-Jan-26

INTRODUCTION

Plant nutrients are fundamental for growth, development, and the monitoring of essential physiological processes. Adequate nutrient availability is therefore critical to sustain plant health, optimize growth, and maximize productivity (Khasawneh et al., 2022; Singh et al., 2022; Kirkby, 2023). Root uptake via soil drench application varies by plant stage, nutrient type, pH and root diseases. The leaves' absorption via the foliar application method offers a rapid solution for correcting nutrient deficiencies. Nonetheless, plant responses to foliar fertilizers and the metabolic activity after uptake are influenced by several factors, including plant surface, chemical formulations and concentrations applied (Januszkiewicz et al., 2025; Wu et al., 2025). Detecting and monitoring plant nutritional status is essential for optimizing fertilization practices and ensuring long-term crop performance. Traditionally, nutrient analysis has depended on destructive laboratory techniques, such as chemical extraction from leaf tissue, which require leaf removal and demand considerable time and cost (Kirkby, 2023; Pandey et al., 2023). While effective, these methods are time-consuming, expensive, and often impractical for large-scale or continuous monitoring of vegetation health (Pandey et al., 2023). As an alternative, advanced sensing technologies (particularly remote sensing of canopy and leaf reflectance) offer a rapid, non-destructive means to

Cite this Article as: Obeidat WM, Othman YA and Al-Zaben NM, 2026. Fertilization-induced changes in leaf nutrient composition and canopy reflectance of *Gardenia jasminoides* in the visible and near-infrared spectrum. International Journal of Agriculture and Biosciences 15(3): 1034-1043. https://doi.org/10.47278/journal.ijab/2026.022

A Publication of Unique Scientific Publishers

detect nutrient status. Variations in reflectance characteristics (e.g., changes in leaf greenness, yellowing, or bleaching) can serve as indicators of nutrient availability and uptake, enabling more efficient monitoring and management of plant health (Pandey et al., 2023; Zahir et al., 2024).

Modern agriculture seeks to manage fertilizer inputs sustainably, balancing economic efficiency with environmental protection (Siedliska et al., 2021). A major challenge for precision farming is the accurate detection and monitoring of plant physiological responses, particularly those linked to nutrient deficiencies. Previous studies have demonstrated that hyperspectral reflectance indices can be used non-destructively to assess plant physiological performance under varying environmental conditions (Othman et al., 2015; Obeidat et al., 2018; Singh et al., 2022). Canopy reflectance indices are effective in detecting a range of biophysical changes associated with pale green leaf coloration, including reductions in photosynthetic efficiency, chlorophyll a, chlorophyll b, and total chlorophyll (a + b) concentrations (Blackburn, 1998; Datt, 1998), alterations in nitrogen status (Bronson et al., 2005), and variations in relative water content (Peñuelas et al., 1994; Gamon & Surfus, 1999). In particular, chlorophyll concentration can be estimated simply, robustly, and non-destructively from leaf spectral reflectance in the red and far-red wavebands.

Remotely sensed data derived using hyperspectral imaging offers a promising approach for detecting nutrient imbalances, including changes in leaf nutrient levels across different plant growth stages (Siedliska et al., 2021). Yellow leaf coloration (chlorosis) is associated with iron nitrate deficiency. Pigments accumulation with reddish or purple discoloration occurs from stress induced by phosphate or nitrate. Under optimal conditions, healthy plants exhibit a consistent green coloration (Obeidat et al., 2018; Wu et al., 2021). The spectral reflectance indices vary according to plant health and nutritional status, with near-infrared (NIR) wavelengths (700-1200nm) being highly predictive of nitrogen (N) content (Bulacio Fischer et al., 2025). Spectral reflectance indices hold promises for detecting nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and iron (Fe) status, as well as pigment concentrations in various plant species (Mahajan et al., 2021; Zahir et al., 2024). N levels are most effectively detected in the wavelength ranges 400-450nm, 530-580nm, 600-690nm, 730-780nm, 810-870nm, and 905-970nm; P levels in 400-470nm, 500-530nm, 690-700nm, and 720-780nm; and K levels in 400-450nm and 600-700nm (Zahir et al., 2024). Additionally, specific normalized difference indices (NDIs) have been developed for other nutrients: Ca using (R883 – R956)/ (R883 + R956), Mg using (R338 – R806)/ (R338 + R806), and Fe using (R531 – R863)/ (R531 + R863) (Mahajan et al., 2021). Healthy plants typically exhibit low reflectance in the visible spectrum and high reflectance in the NIR range (Obeidat et al., 2018; Zahir et al., 2024). Singh et al. (2022) reviewed studies from 2010–2020 on NIR spectroscopy and hyperspectral remote sensing for foliar nutrient detection, confirming that these technologies deliver reasonably accurate results when combined with effective pre-processing and robust statistical models to minimize spectral noise. Factors such as sample size, number of latent variables, and leaf water content influence prediction accuracy, while epicuticular waxes and trichomes may also affect leaf optical properties. Pandey et al. (2023) demonstrated that partial least squares regression (PLSR) models applied to hyperspectral data can accurately predict N, P, K, and sulfur (S) concentrations (R^2 = 0.60–0.88) in hydroponically grown lettuce, with lower accuracy for Ca and Mg (R^2 = 0.12–0.34). Nutrient deficiency classification models showed high accuracy for N, P, and S (F1-scores = 0.71-1.00), but less consistent results for K, Ca, and Mg, particularly K (F1-scores = 0.40-0.67). Overall, these findings highlight hyperspectral imaging as a powerful, non-destructive tool for assessing plant nutrient status.

Gardenia (*Gardenia jasminoides*) is a valuable ornamental species whose growth, flowering performance, and yield are highly dependent on the level and method of fertilizer application (Othman et al., 2015; Shalaby, 2024; Sokolowski et al., 2025). Fertilization practices directly influence the availability of key nutrients (N, P, K, Ca, Mg, and Fe), which play essential roles in supporting plant development and flower quality (Shalaby & Ramadan, 2024; Sokolowski et al., 2025). A persistent challenge for gardenia growers is the inconsistent application of nutrient solutions, and the limited understanding of how the two common fertilization methods (foliar spraying and soil drenching) differentially affect nutrient uptake, growth, and flowering. Conventional nutrient analysis techniques are destructive, labor-intensive, and costly, limiting their practicality for routine monitoring. In contrast, hyperspectral remote sensing offers a rapid, non-destructive alternative by detecting changes in canopy and leaf reflectance associated with nutrient status. Although previous research has largely focused on using spectral reflectance to detect N due to its central role in plant productivity (Singh et al., 2022; Othman & Leskovar, 2024), limited studies have examined its potential for detecting other macronutrients (P, K, Ca, Mg) and micronutrients such as Fe.

Addressing this gap, the present study investigates the relationship between fertilization method, nutrient uptake, and spectral reflectance in gardenia. Specifically, it compares the effects of foliar and soil drench applications on the concentrations of N, P, K, Ca, Mg, and Fe in leaves; evaluates the impact of application method on canopy-level spectral characteristics; and explores correlations between leaf nutrient concentrations and spectral reflectance to identify potential hyperspectral indicators for real-time, non-destructive nutrient monitoring. The integration of hyperspectral reflectance offers a significant opportunity to improve nutrient management in crop production. Understanding the spectral reflectance signatures associated with different nutrient levels and how fertilization methods impact these signatures, as well as nutrient uptake, can lead to more precise and efficient fertilization practices, thereby reducing the need for traditional, destructive analysis.

MATERIALS & METHODS

Trial Locations, Plant Materials, and Treatments

The experiment was conducted in a greenhouse at the University of Jordan from January to October 2023. One-year-old gardenia (*Gardenia jasminoides* cv. 'Fortuniana') plants were used. Each transplant was grown in 15L pot filled with a growing substrate composed of clay, peat moss, and sand in a ratio of 1:2:1(v/v/v). The substrate had an electrical conductivity of 0.5±0.2dS m^{-1} and a pH of 7.2±0.3. Throughout the experimental period, the greenhouse was partially monitored (specifically, temperature) with mean minimum and maximum temperatures of 19°C and 25°C, respectively. Relative humidity ranged from 55% to 65%. Average daytime photosynthetic photon flux density (PPFD) was 1230±50μmol m^{-2} s^{-1}.

Two fertilization methods (foliar spraying and soil drenching) were evaluated during the experimental period. In both treatments, the nutrient solution had the same final composition (mg L^{-1}): 150 N, 70 P, 200 K, 70 Ca, 50 Mg, 5 Fe, 2 B, 2 Cu, 5 Zn, and 5 Mn. The pH of the solutions was adjusted to 7.0 before application. Fertilizers were applied once every two weeks, with macronutrients (N–P–K) and micronutrients applied in the first week, and Ca and Mg supplied in the second week to minimize nutrient interactions. For foliar application, plants were irrigated with water before spraying to ensure uniform leaf wetting, after which 400mL of nutrient solution was applied to the canopy using a handheld pressure sprayer. For soil drenching, 400mL of nutrient solution (pH-adjusted (7-6.5)) was applied directly to the substrate around the plant base. The experiment was conducted in the greenhouse using RCBD with two fertilization treatments. Each treatment consisted of four replicates, with five pots per replicate.

Measurements

Both treatments were applied consistently for seven consecutive months to ensure full plant response and allow sufficient time for differences between treatments to become evident. This period ensured that the effects of fertilization were stabilized and clearly reflected in plant growth and nutrient uptake. After this period, all spectral and laboratory analyses were conducted following standard protocols. To ensure accuracy, leaf nutrient sampling and hyperspectral canopy reflectance measurements were performed on the same day. For nutrient analysis, gardenia leaf samples (four replicates per treatment) were oven-dried at 65°C and ground into a fine powder. A 0.5g subsample was digested with a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$), consisting of 5mL of 70% HNO_3 and 1.5mL of 60% $HClO_4$, until the brown fumes were completely released. After cooling, the digest was diluted in a 1:1 ratio with 5mL of hydrochloric acid (HCl), filtered, and further diluted with distilled water to a final volume of 25mL. Concentrations of N, P, K, Ca, Mg, and Fe were determined using inductively coupled plasma optical emission spectrometry (ICP-OES 7000, Thermo Fisher Scientific Inc., Waltham, MA, USA), following the procedures of Masson et al. (2010) and Van Acker et al. (2023).

Canopy spectral reflectance in the range of 350-1100nm was measured under clear-sky conditions outside of the greenhouse at a specific location between 11:00 and 13:00 using a portable spectroradiometer (FieldSpec® HandHeld 2, Analytical Spectral Devices, Boulder, CO, USA). Measurements were taken 20cm above the plant canopy in full sunlight at 3-nm spectral resolution. Due to the low signal-to-noise ratio below 400nm and above 950nm, analyses were restricted to the 400-950nm range. A white reference standard plate was used for calibration before scanning each plant, and reflectance at each wavelength was calculated as the ratio of the detector signal from the canopy surface to that from the reference standard. For each replicate, the spectral data point represented the mean of five scans taken from five individual plants. A total of four replicates were analyzed for both foliar spray- and drench-treated plants. From the processed reflectance spectra, spectral indices were calculated, including all possible normalized difference indices (NDIs) derived from wavelength pair combinations (equation 1).

All possible normalized difference indices (NDIs) were also explored for all wavelength pairs at 3nm intervals in the reflectance spectra. The proportion of variance in plant nutrient concentrations (N, P, K, Ca, Mg, Fe) explained by each index was plotted into a matrix and converted into a heat map using R statistical software.

$$NDI = \frac{R_{i+3nm} - R_i}{R_{i+3nm} + R_i} \quad \text{Equation 1}$$

Where R_i is leaf reflectance at wavelength i.

Statistical Analysis

Statistical analyses were performed using the PROC GLIMMIX procedure in SAS (Version 9.4 for Windows; SAS Institute, Cary, NC, USA). The experiment followed a randomized complete block design with four replicates; the mean of five subsamples per replicate was used for this analysis. The total variance was partitioned into different effects replication and treatment. Fertilization treatments were considered fixed effects, and replications were considered as random effects. Each trait was fitted to the following model:

$$y_{ij} = \mu + T_i + R_j + \varepsilon_{(ij)}$$

Where: y_{ij} denotes the value of trait of the i^{th} treatments, in the j^{th} replications. The term μ is the grand mean, T_i is the treatment effect, R_j is the effect of the j^{th} replication, and $\varepsilon_{(ij)}$ is the residual.

The Shapiro-Wilk statistic of PROC UNIVARIATE in SAS was used to test for normality of the distribution of errors and ensure the mean of residuals equaled to zero. A two-way analysis of variance (ANOVA) was conducted, and treatment means were separated. Post-hoc multiple comparisons were performed using the Least Significant Difference (LSD) test at a significant level of $P \leq 0.05$

RESULTS

Leaf Mineral Nutrient under Foliar Spraying and Soil Drenching

Leaf nutrient concentrations of *Gardenia jasminoides* cv. 'Fortuniana' varied significantly between the two fertilizer application methods (Table 1). Plants treated with soil drench showed significantly higher concentrations of N, Ca, and P compared to those treated with foliar spray ($P \leq 0.05$). In contrast, foliar spray resulted in significantly higher levels of Mg and Fe, with Fe nearly doubling under foliar treatment (160mg kg^{-1}) compared to soil drench (89.2mg kg^{-1}). Potassium levels did not differ significantly between treatments. Regarding nutrient ratios, the N:K ratio was significantly higher in soil drench plants (1.29) than in foliar spray (0.65), while the K:Ca ratio was significantly higher under foliar spray (2.01) than soil drench (1.20). The Ca:Mg ratio also differed, being higher in soil drench (2.38) than in foliar spray (1.29). No significant differences were observed in N:P or K:Mg ratios. These results indicate that fertilizer application method influences both individual nutrient accumulation and nutrient balance in gardenia leaves.

Table 1: Leaf nutrient concentrations of *Gardenia jasminoides* cv. 'Fortuniana' under two fertilizer application methods, soil drench and foliar spray

Nutrient	Soil drench	Foliar Spray	P-value
N (mg kg^{-1})	14913±887	7792±478	0.0004
Ca (mg kg^{-1})	10312±1539	6213±754	0.05
Mg (mg kg^{-1})	4356±82	4837±81	0.006
K (mg kg^{-1})	11571±378	11980±290	0.42
Fe (mg kg^{-1})	89.2±2.9	160±10.9	0.0008
P (mg kg^{-1})	1775±52.4	993±41.8	0.0001
N: P	8.41±0.51	7.88±0.50	0.48
N: K	1.29±0.07	0.65±0.06	0.0003
Ca: Mg	2.38±0.39	1.29±0.18	0.04
K: Ca	1.20±0.18	2.01±0.23	0.03
K: Mg	2.66±0.07	2.48±0.05	0.07

Each value (mean±SE) were calculated from four replicates per treatment. Differences between Drench and Foliar treatments with P≤0.05 are considered statistically significant.

Canopy Surface Reflectance under Foliar Spraying and Soil Drenching

Fig. 1 illustrates the mean canopy spectral reflectance of Gardenia jasminoides cv. 'Fortuniana' grown under two fertilizer application methods: soil drenching and foliar spray. Significant differences in reflectance ($P \leq 0.05$) were observed across the 400-700nm range. Plants treated with foliar spray exhibited consistently higher reflectance in the visible spectrum (400-700nm), compared to soil-drenched plants. In contrast, reflectance in the near-infrared (NIR) region was higher in soil-drenched plants compared to foliar spray within the 700 to 730nm wavelengths.

Normalized Difference Indices (NDIs) were computed for all possible wavelength combinations across the spectral range (400-950nm) and correlated with leaf nutrient concentrations (N, P, K, Ca, Mg, and Fe) in gardenia plants under two fertilization treatments: foliar spraying and soil drenching (Fig. 2). In plants receiving foliar spray, the NDIs most strongly associated with leaf N were concentrated in specific spectral regions, particularly in the 652-694nm and 715-745nm ranges. For example, the NDI constructed from 658 nm and 742 nm showed a strong correlation with N (r^2 = 0.93). Similar strength was observed for NDIs combining red wavelengths with NIR (750-890nm), such as 658nm and 853nm (r^2 = 0.94), and for combinations involving water absorption wavelengths (900-950nm), such as 658 nm and 937 nm (r^2 = 0.86). The strongest correlations appeared in NDIs formed from pairings of wavelengths of 433nm and 460nm (r^2 = 0.98) as well as 433nm and 670nm (r^2 = 0.97). Under soil drenching, high correlations with N were identified for NDIs combining blue bands (400-436nm) with NIR wavelengths (709-745nm), such as 415nm and 721nm (r^2 = 0.86). Also, NDIs using the green band at 556 nm paired with NIR bands 736nm (r^2 = 0.86) or 868nm (r^2 = 0.89) showed strong relationships. The highest overall correlation for soil drenching was observed for the NDI combining 781nm and 943nm, with an r^2 of 0.99.

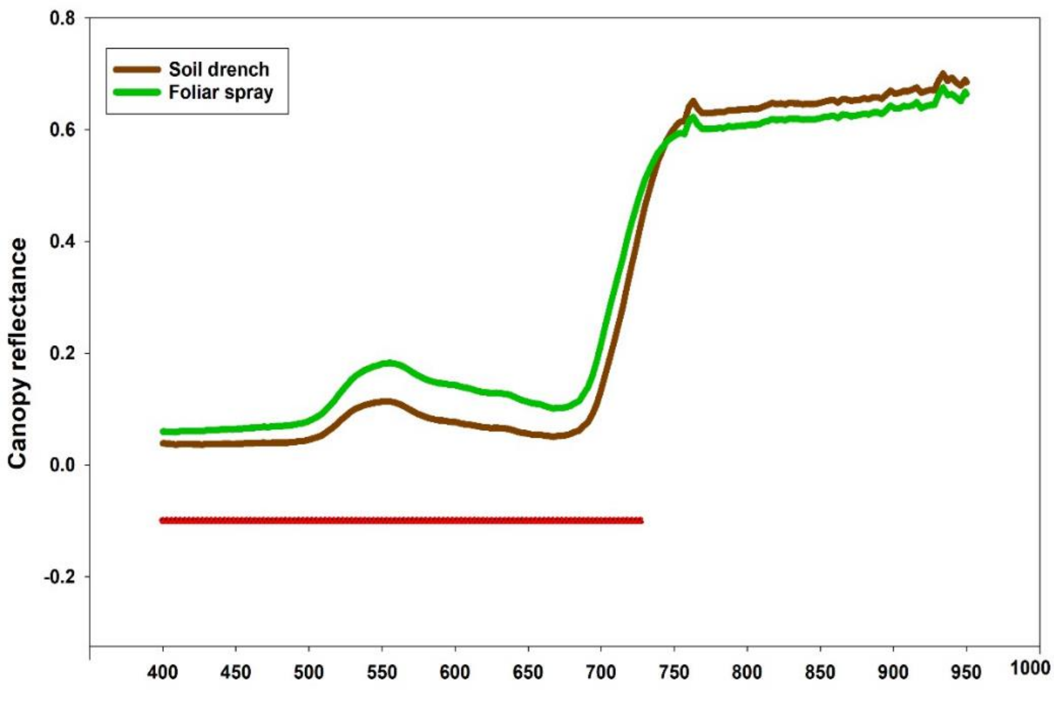

Fig. 1: Mean canopy spectral reflectance of *Gardenia jasminoides* cv. 'Fortuniana' grown under two fertilizer treatments. Data are for soil drenching (brown line) and foliar spray (green line) treatments. Bottom red line indicates a significant P-value at P≤0.05.

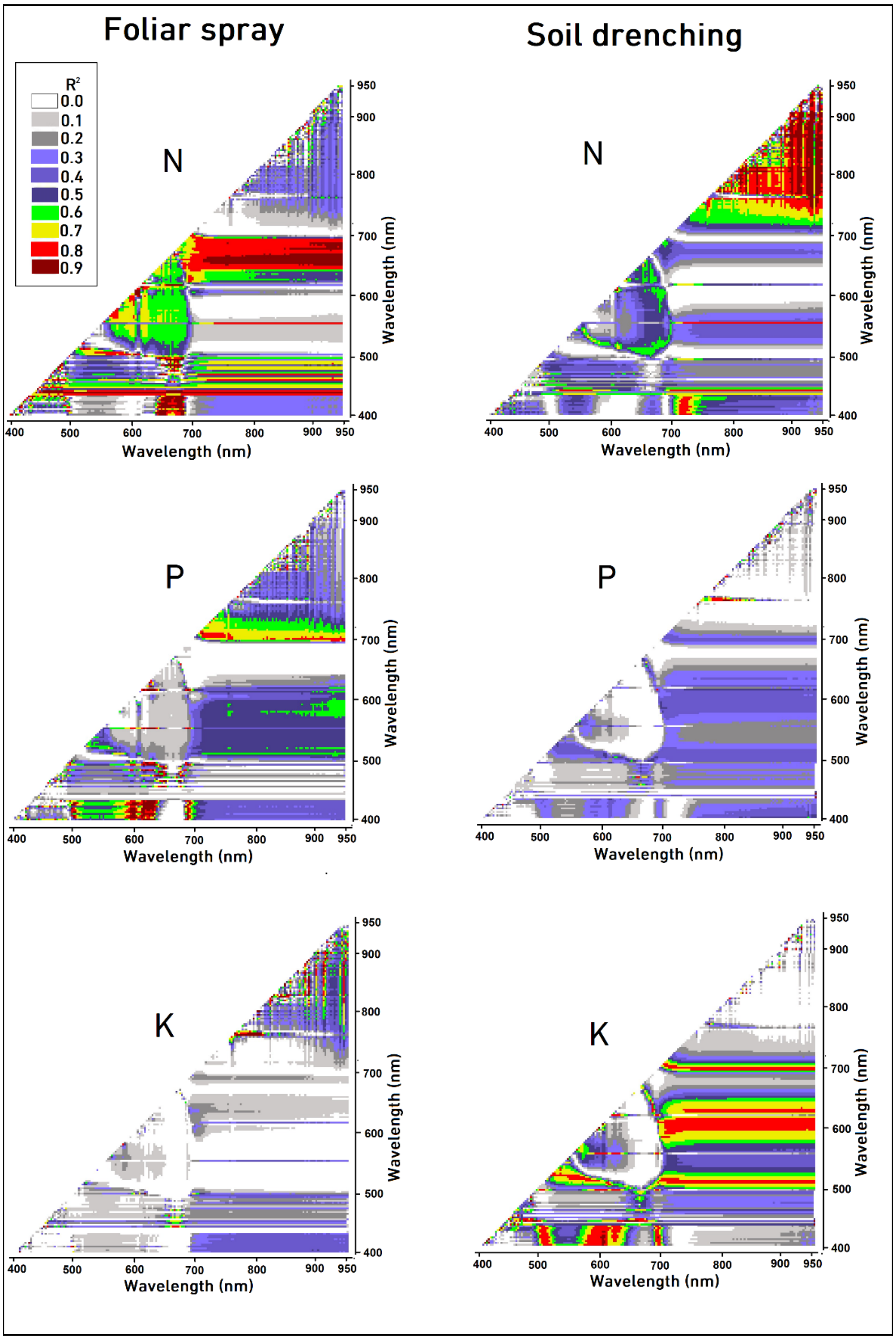

Fig. 2: Heat maps displaying r^2 values were generated by regressing leaf mineral nutrients (N, P, K) against the canopy spectral reflectance of *Gardenia jasminoides* cv. 'Fortuniana,' grown under two fertilizer treatments: soil drenching and foliar spray. Analyses included all possible normalized difference indices created from pairs of reflectance means at 3-nm intervals between 400 and 1000nm.

For P (Fig. 2), the foliar spray treatment showed strong correlations between NDIs built from 406-430nm and 505-511nm wavelengths, such as 406nm and 511nm (r^2 = 0.99). High correlations also noticed in the 406-430nm and 600-650nm combination (e.g., 415 and 607nm, r^2 = 0.96; 421 and 631nm; r^2 = 0.97). Under soil drenching treatment, P was highly correlated with NDIs made from NIR pairs, specifically 763nm and 805nm (r^2 = 0.98). K content in gardenia plants subjected to foliar spray treatment (Fig. 2) showed strong correlations with NDIs constructed from infrared wavelength pairs in the 760-766 and 766-808nm ranges, such as 763nm and 799nm (r^2 = 0.99). Additional high correlations were observed between NDIs in the 820-920nm range ($0.85 \leq r^2 \leq 0.97$). Under soil drenching treatment, high correlations between NDIs combining 400-420nm and 580-600nm as well as 850-610nm and 720-950nm ($0.85 \leq r^2 \leq 0.95$).

The relationship between leaf Ca concentration and canopy spectral reflectance in gardenia plants under foliar spraying and soil drenching treatments is shown in Fig. 3. Under foliar spray, strong correlations were found between NDIs using wavelengths from 406-433nm and 550-620nm, such as 430nm and 600 nm (r^2 = 0.96). Additional high correlations appeared for NDIs combining Notable pairings included 680-720 and wavelength within the 700-950nm ($0.8 \leq r^2 \leq 0.95$). In soil drenching treatment, strong correlations were observed between NDIs combining blue wavelengths (436-439nm) with bands in the 499-950nm range ($0.90 \leq r^2 \leq 0.98$) (Fig. 3). NDIs in the 856-907nm range also showed high correlation with water absorption wavelengths at 928-931nm (e.g., 868nm and 928nm; r^2 = 0.99).

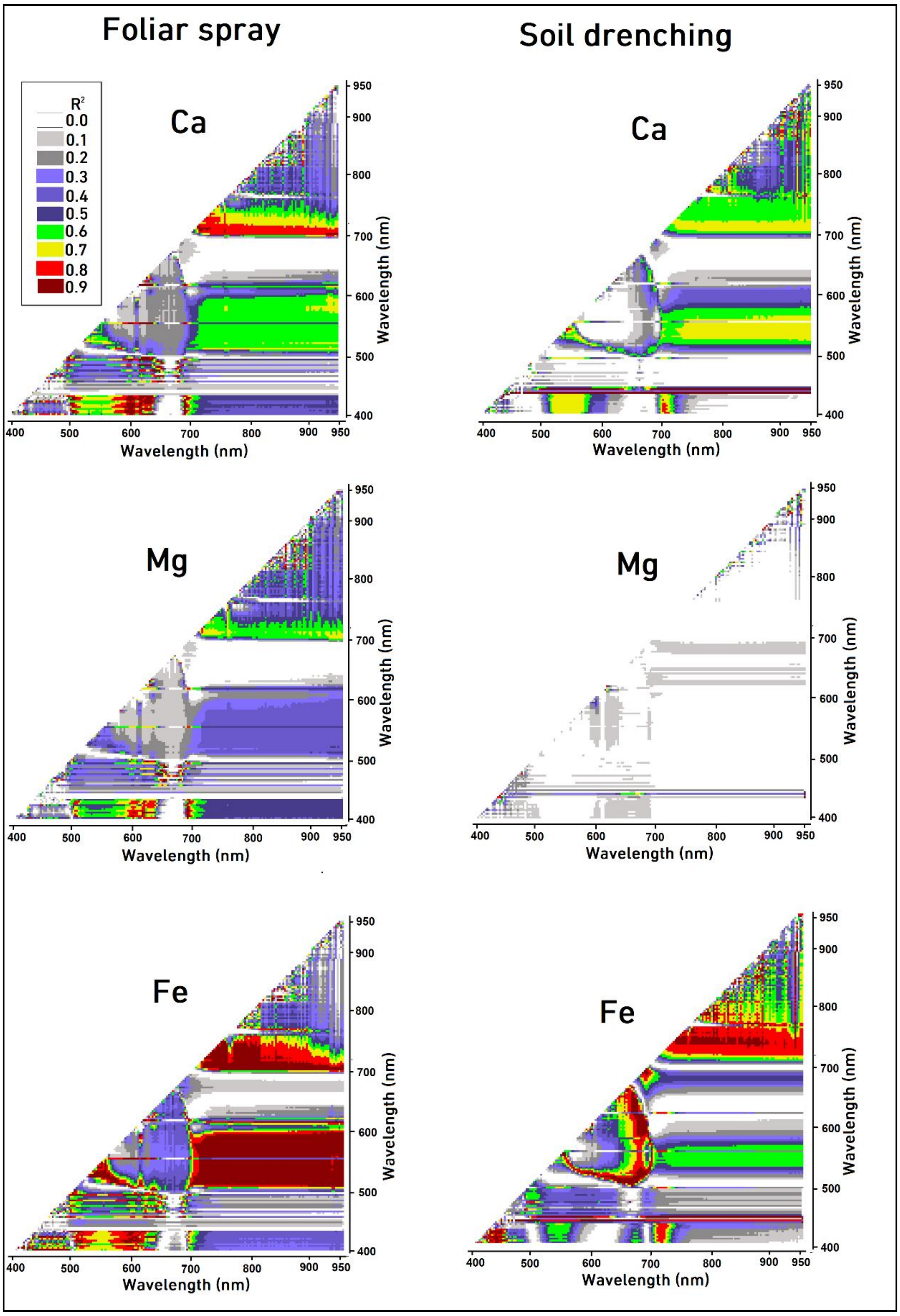

Fig. 3: Heat maps displaying r^2 values were generated by regressing leaf mineral nutrients (Ca, Mg, Fe) against the canopy spectral reflectance of *Gardenia jasminoides* cv. 'Fortuniana,' grown under two fertilizer treatments: soil drenching and foliar spray. This analysis included all possible normalized difference indices created from pairs of reflectance means at 3-nm intervals between 400 and 1000nm.

Gardenia plants treated with foliar spray showed strong correlations between leaf Mg concentration and NDIs constructed from specific wavelength combinations (Fig. 3). High correlations were found between NDIs in the combination of 406-430nm and 580-640nm ranges, such as between 412nm and 628nm (r^2 = 0.99). In the infrared region, strong correlations were observed between 760-766nm and 802-862nm, such as 817nm and 856nm (r^2 = 0.93), 832nm and 871nm (r^2 = 0.96), and 832nm and 889nm (r^2 = 0.96). In contrast, Mg content in plants under soil drenching showed only low to moderate correlation, indicating reduced sensitivity compared to foliar treatment.

Iron concentration in gardenia exhibited strong correlations with various NDIs under both foliar spraying and soil drenching treatments, particularly within the near-infrared (NIR) spectral bands (Fig. 3). In the foliar spray treatment, NDIs combining wavelengths in the 400–420nm and 560-610nm ranges showed a very high correlation with Fe. Similarly, NDIs constructed from combinations of 510-590nm with 710-950nm, and 700-720nm with 710-850nm, also demonstrated strong relationships ($0.90 \leq r^2 \leq 0.98$). Under soil drenching conditions, high correlations were observed for NDIs using wavelengths at 418nm and 442nm (r^2 = 0.97), 431nm and 715nm (r^2 = 0.88), and 445nm and 928nm (r^2 = 0.94). Additionally, NDIs combining wavelengths in the 700-720nm and 710-850nm ranges consistently showed strong correlations across both treatments ($0.90 \leq r^2 \leq 0.98$).

DISCUSSION

Mineral Nutrient under Foliar Spraying and Soil Drenching

The comparison between soil drench and foliar spray treatments revealed clear differences in nutrient uptake by plant leaves (Table 1). Soil drenching significantly increased the concentrations of key macronutrients such as N, P, and Ca, indicating that root-based fertilization is more effective for supplying these relatively immobile or soil-available nutrients (Hawkesford et al., 2023). This response reflects enhanced root uptake and nutrient mobility within the rhizosphere, where N in nitrate form is readily absorbed, P availability is improved through localized application that minimizes fixation losses, and Ca is efficiently translocated via the xylem with transpiration flow. In contrast, foliar application resulted in higher Mg and Fe concentrations, demonstrating that direct leaf absorption provides a more efficient pathway for nutrients that are less mobile in the soil or easily precipitated under alkaline conditions (Ishfaq et al., 2022). The ability of Mg and Fe to penetrate the leaf cuticle and stomata allows rapid assimilation and bypasses soil-related constraints such as high pH and ionic antagonism (Ishfaq et al., 2022). Collectively, these results highlight the complementary roles of soil and foliar fertilization, where soil drenching enhances macronutrient acquisition through root uptake, while foliar feeding effectively improves micronutrient availability and leaf metabolic function.

K concentrations did not differ significantly between treatments, indicating that both methods were equally effective in supplying this nutrient. Recent research on soil fertility and plant nutrition has increasingly focused on the biochemical processes governing nutrient availability and plant uptake (Khasawneh et al., 2022; Hartemink & Barrow, 2023; Al-Kofahi et al., 2025). Among nutrient delivery methods, foliar application is valued for its rapid and immediate effects, as nutrients are quickly absorbed through leaf tissues (Jamal et al., 2006). However, its impact is often short-lived due to limited nutrient retention and internal mobility (Jamal et al., 2006). In contrast, soil drenching, which involves applying diluted nutrient solutions directly to the root zone, allows extended contact between roots and nutrients, resulting in gradual absorption and sustained translocation to stems, branches, and leaves (Youssef et al., 2022). Othman and Al-Zaben (2025) found that nutrient drenching at pH 6 significantly improved plant performance compared to foliar spraying at the same pH, with increases of 90% in chlorophyll content, 200% in leaf area, 84% in leaf fresh weight, and 155% in flower number. However, it also caused reductions in root fresh weight (−42%), leaf nutrient levels (−47%), and soil respiration (−15%), highlighting potential physiological trade-offs of the method.

A balanced supply of essential nutrients is fundamental to improving plant productivity, as interactions among nutrients (whether synergistic, antagonistic, or neutral) play a key role in regulating plant growth, nutrient uptake, and physiological responses (Fageria, 2001). These interactions are commonly evaluated through changes in biomass accumulation and nutrient concentrations following the combined application of different nutrients. Understanding these complex relationships is crucial for developing effective nutrient management strategies in agricultural systems. In this context, nutrient ratios such as N:P, N:K, Ca:Mg, K:Ca, and K:Mg serve as practical diagnostic tools to assess nutritional balance, physiological function, and potential deficiencies. For instance, the N:P ratio (optimal around 7.5:1) reflects the balance between N, vital for vegetative growth, and P, essential for root development and energy transfer; deviations from this ratio may indicate nitrogen excess or phosphorus limitation (Hawkesford et al., 2023; Kirkby, 2023). The N:K ratio (~ 1.5:1) illustrates the relationship between N-driven growth and K-mediated stress tolerance and fruit development, with higher ratios potentially impairing reproductive success. The Ca:Mg ratio (~2.5:1) indicates the balance between calcium's structural role and magnesium's function in photosynthesis, where imbalances can limit nutrient uptake. Similarly, the K:Ca (2:1) and K:Mg (5:1) ratios reflect competitive uptake dynamics, where excess K may suppress Ca or Mg absorption, potentially resulting in disorders like blossom-end rot or chlorosis (Hawkesford et al., 2023). Thus, maintaining nutrient ratios within optimal ranges is essential for sustaining plant health, maximizing growth, and preventing nutrient antagonism (Hawkesford et al., 2023; Kirkby, 2023).

The comparison of nutrient ratios between soil drench and foliar spray treatments reveals distinct differences in nutrient balance relative to standard optimal ranges. The N:P ratio was slightly above the recommended 7.5:1 in both treatments (8.41 for soil drench and 7.88 for foliar spray), suggesting a marginal P limitation or excess N uptake, with no significant difference between methods. The N:K ratio under soil drench (1.29) was closer to the ideal 1.5:1, indicating a more balanced N and K supply, while the lower ratio in foliar spray (0.65) suggests a relative K surplus or reduced N assimilation. In terms of Ca:Mg, soil drench (2.38) closely matched the optimal 2.5:1 ratio, supporting adequate Ca and Mg balance, whereas foliar spray (1.29) deviated notably, indicating a potential Ca deficiency. The K:Ca ratio was more favorable under foliar spray (2.01), aligning with the optimal 2:1 value, while the soil drench (1.20) fell below, suggesting a K limitation relative to Ca. Finally, both treatments exhibited suboptimal K:Mg ratios (2.66 for soil drench and 2.48 for foliar spray) compared to the recommended 5:1, indicating a potential excess of Mg or insufficient K supply. Overall, soil drench provided better alignment with ideal N:K and Ca:Mg ratios, while foliar spray more closely matched the desired K:Ca balance, highlighting the distinct nutrient delivery profiles of each fertilization method.

Canopy Surface Reflectance under Foliar Spraying and Soil Drenching

Hyperspectral remote sensing is emerging as a promising non-destructive tool for the rapid diagnosis of plant growth and nutrient status (Feng et al., 2020). This approach is valued for its speed, stability, and strong correlation between canopy parameters and plant nutrient levels (Feng et al., 2020; Qarallah et al., 2022). With ongoing advancements in remote sensing technologies, its application in real-time monitoring of plant nutrition is expected to grow significantly (Feng et al., 2020). In this study, mean canopy surface reflectance in the visible spectrum (400-700nm) was significantly higher ($P \leq 0.05$) in gardenia plants treated with foliar spray compared to those receiving soil drenching (Fig. 1). In contrast, plants under soil drenching exhibited higher reflectance in the NIR (700-950nm) region. Soil-drenched plants also had greater leaf concentrations of N, Ca, and P, whereas foliar-sprayed plants showed elevated Fe and Mg levels (Table 1). The increased visible reflectance in foliar-sprayed plants can be attributed to lower N content, reducing chlorophyll synthesis and thus decreasing absorption of red and blue light while increasing green-light reflectance, a common trait in N-deficient foliage (Singh et al., 2022). Although foliar-sprayed leaves had higher Fe concentrations, this micronutrient alone is insufficient to increase chlorophyll content in the presence of limited N. Moreover, surface-deposited Fe can increase specular reflectance without enhancing internal pigmentation (Nasar et al., 2022). Conversely, higher NIR reflectance from soil-drenched plants is linked to their elevated N, Ca, and P content, promoting thicker, well-hydrated mesophyll and structurally stronger cell walls. Higher Ca levels enhance middle lamella thickness and cell wall electron density, increasing internal NIR scattering (Falcioni et al., 2020). Thus, leaves from foliar-sprayed plants, characterized by lower N and Ca levels, likely remained thinner, reducing NIR reflectance. Overall, nutrients influencing chlorophyll content (e.g., N) decrease visible reflectance, while those enhancing structural integrity (e.g., Ca) elevate NIR reflectance, explaining the observed differences between fertilization methods.

The higher spectral reflectance observed in foliar-sprayed plants within the visible and lower reflectance in the NIR compared to soil-drenched plants could be also linked to decreased leaf area and more vertical leaf orientation. Foliar spraying reduced leaf N levels, limiting chlorophyll synthesis and leaf expansion, and caused leaves to adopt a more upright orientation, thus influencing light penetration through canopy (Othman & Leskovar, 2024; Othman & Al-Zaben, 2025). Othman and Leskovar (2024) demonstrated that tomato plants grown under low N supply (10 mg L^{-1}) exhibited more erect leaves (mean tilt angles ranging from 54.3° to 73.6°) and higher canopy light penetration compared to plants with adequate N (50-300mg L^{-1}; mean tilt angles of 36.4°-51.9°). High N fertigation (300mg L^{-1}) substantially increased leaf area index (LAI; 3.6- to 4.9-fold), canopy NDVI, and leaf N concentration (2- to 3-fold) compared to the lowest N rate. Consequently, foliar-sprayed gardenia plants, characterized by lower N supply, exhibited higher canopy light penetration and, consequently, lower NIR reflectance relative to soil-drenched plants.

Sustainable fertilizer management is crucial in precision agriculture to ensure both economic efficiency and environmental protection. To optimize fertilizer use, various strategies have been developed to assess and monitor plant nutrient status, including the use of controlled-release fertilizers and partial fertilization application techniques that match nutrient supply with crop demand (Khasawneh et al., 2022; Othman & Al-Zaben, 2025). Among the advanced monitoring tools, hyperspectral imaging has gained increasing attention due to its ability to detect subtle physiological and biochemical changes in plants, reflecting variations in environmental conditions and nutrient availability (Okyere et al., 2023). This technology offers a non-destructive, real-time approach to support informed decision-making in nutrient management. Several research studies have focused on detecting major macronutrients using remote sensing technologies, with particular emphasis on N due to its central role in plant health and productivity (Singh et al., 2022; Othman & Leskovar, 2024). In contrast, relatively few studies have investigated the remote sensing-based detection of other macronutrients (such as P, K, Ca, Mg) or important micronutrients like (Mn, Fe, and Zn). This study addresses a critical gap in precision agriculture by exploring the relationship between hyperspectral reflectance and a broader range of nutrients beyond N, including P, K, Ca, Mg, and Fe. By identifying key spectral regions associated with each nutrient, the research enhances the potential for non-destructive, multi-nutrient monitoring using remote sensing. The analysis of spectral correlations with mineral nutrients under foliar spraying and soil drenching treatments (Fig. 2 and 3) revealed key overlapping wavelength regions that can guide the development of targeted spectral indices for future nutrient evaluation in gardenia. Under foliar spray, the 400-430nm range consistently showed high correlations with multiple nutrients including P, Ca, Mg, and Fe, indicating its strong potential for detecting nutrient-related variations in the blue-violet spectrum. Similarly, the 580-640nm region (green to red edge) was effective for P, Mg, and Ca, suggesting its relevance in evaluating leaf pigmentation changes linked to nutrient status. Additionally, the 700-850nm NIR bands were highly correlated with N and Fe, making them suitable for assessing chlorophyll-related responses and internal leaf structure. In contrast, under soil drenching, the most consistent and informative spectral overlaps were found within the 700-950nm range, especially for N, P, K, and Fe. This region captures key NIR responses associated with internal leaf water and nutrient transport mechanisms. The 400-420nm range, although less dominant than in foliar treatments, still contributed significantly to the detection of P, K, and Ca when paired with NIR wavelengths. Importantly, Ca and Fe both showed strong correlations in the 928-931nm water absorption region, indicating that spectral indices in this range could provide dual insights into nutrient and water status.

Overall, the overlapping regions of 400-430nm and 580-640nm (visible) for foliar spray, and 700-950 nm (NIR) for soil drenching, emerge as robust spectral zones for future nutrient monitoring. These ranges can be prioritized in the design of hyperspectral or multispectral sensing tools for precise, non-destructive evaluation of nutrient dynamics under different fertilization strategies.

Limitations

Despite the promising outcomes, this study has certain limitations, as it was conducted on a single *Gardenia jasminoides* cultivar under controlled environmental conditions. Such factors may limit the general applicability of the spectral–nutrient relationships observed, since canopy structure, pigment composition, and nutrient uptake efficiency can vary among cultivars and environments. Seasonal and environmental fluctuations in temperature, humidity, and light intensity may also influence spectral responses. Therefore, further validation across different cultivars, seasons, and growth environments is necessary to confirm the robustness and transferability of these findings. Multi-seasonal and multi-site assessments, combined with advanced modeling approaches, will enhance the reliability of hyperspectral techniques for nutrient diagnosis and precision horticultural management.

Conclusion

This study bridges a critical gap in precision agriculture by investigating the relationship between hyperspectral reflectance and a broad spectrum of essential mineral nutrients, moving beyond the traditional focus on N. While N has been extensively studied due to its central role in plant productivity, other vital nutrients such P, K, Ca, Mg, and Fe remain underexplored in remote sensing research. By systematically evaluating the spectral signatures associated with each of these nutrients, this research identifies key wavelength regions that correlate strongly with their concentrations in plant tissues under two contrasting fertilization methods: soil drenching and foliar spray.

The findings highlight the distinct nutrient delivery profiles of each method and their physiological implications. Soil drenching proved more effective in delivering less mobile macronutrients like N, P, and Ca, which was reflected in enhanced canopy NIR reflectance. In contrast, foliar application was more efficient for supplying Mg and Fe, particularly influencing reflectance in the visible range. Hyperspectral analysis revealed that foliar treatments correlated most strongly with reflectance in the 400-430nm, 580-640nm, and 700-850nm bands, while soil drenching showed high correlations within the 700-950nm range, including the water absorption region around 928-931nm.

Together, these results provide a scientific foundation for the development of advanced, non-destructive diagnostic tools using hyperspectral sensing to enable real-time, multi-nutrient assessment in plants. This approach enhances nutrient use efficiency, supports sustainable fertilizer management, and minimizes environmental impacts. Future research should focus on refining and validating these spectral indices across species and growing conditions, paving the way for their integration into decision-support systems within precision agriculture frameworks.

DECLARATIONS

Funding: The Authors would like to express gratitude to the Deanship of Scientific Research at the University of Jordan for their financial support (grant number 2553), which covered the costs of essential materials required for the mineral analysis, as well as other laboratory supplies.

Acknowledgement: The authors gratefully acknowledge the support of the Deanship of Scientific Research at the University of Jordan.

Conflict of Interest: None.

Data Availability: Data is available upon request.

Ethics Statement: This study did not involve human or animal subjects.

Author's Contribution: Conceptualization, W.M.O and Y.A.O.; methodology, Y.A.O. and N.M.A.; software, W.M.O.; validation, N.M.A. and W.M.O.; formal analysis, W.M.O. and Y.A.O.; investigation, N.M.A.; resources, Y.A.O.; data curation, W.M.O; writing—original draft preparation, W.M.O and Y.A.O. ; writing—review and editing, Y.A.O.; visualization, Y.A.O. and W.M.O.; supervision, Y.A.O.; project administration, Y.A.O. All authors have read and agreed to the published version of the manuscript.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

REFERENCES

Al-Kofahi, S.D., Almrahleh, R.Y., Sawalhah, M.N., & Othman, Y.A. (2025). Yield and physiological responses of wheat (Triticum aestivum L.) in relation to different levels of nutrient. *South African Journal of Botany, 184*, 1051-1061. https://doi.org/10.1016/j.sajb.2025.07.020

Blackburn, G.A. (1998). Quantifying chlorophylls and caroteniods at leaf and canopy scales: An evaluation of some hyperspectral approaches. *Remote Sensing of Environment, 66*(3), 273-285. https://doi.org/10.1016/S0034-4257(98)00059-5

Bronson, K.F., Booker, J., Keeling, J.W., Boman, R.K., Wheeler, T.A., Lascano, R.J., & Nichols, R.L. (2005). Cotton canopy reflectance at landscape scale as affected by nitrogen fertilization. *Agronomy Journal, 97*(3), 654-660. https://doi.org/10.1046/j.1469-8137.1999.00424.x

Bulacio Fischer, P.T., Carella, A., Massenti, R., Fadhilah, R., & Lo Bianco, R. (2025). Advances in monitoring crop and soil nutrient status: proximal and remote sensing techniques. *Horticulturae, 11*(2), 182. https://doi.org/10.3390/horticulturae11020182

Datt, B. (1998). Remote sensing of chlorophyll a, chlorophyll b, chlorophyll a+ b, and total carotenoid content in eucalyptus leaves. *Remote Sensing of Environment, 66*(2), 111-121. https://doi.org/10.1016/S0034-4257(98)00046-7

Fageria, V. (2001). Nutrient interactions in crop plants. *Journal of Plant Nutrition, 24*(8), 1269-1290. https://doi.org/10.1081/PLN-100106981

Falcioni, R., Moriwaki, T., Perez-Llorca, M., Munné-Bosch, S., Gibin, M.S., Sato, F., & Rüggeberg, M. (2020). Cell wall structure and composition is affected by light quality in tomato seedlings. *Journal of Photochemistry and Photobiology B: Biology, 203*, 111745. https://doi.org/10.1016/j.jphotobiol.2019.111745

Feng, D., Xu, W., He, Z., Zhao, W., & Yang, M. (2020). Advances in plant nutrition diagnosis based on remote sensing and computer application. *Neural Computing and Applications, 32*(22), 16833-16842. https://doi.org/10.1007/s00521-018-3932-0

Gamon, J.A., & Surfus, J.S. (1999). Assessing leaf pigment content and activity with a reflectometer. *The New Phytologist, 143*(1), 105-117. https://doi.org/10.1046/j.1469-8137.1999.00424.x

Hartemink, A.E., & Barrow, N. (2023). Soil pH-nutrient relationships: the diagram. *Plant and Soil, 486*(1), 209-215. https://doi.org/10.1007/s11104-022-05861-z

Hawkesford, M.J., Cakmak, I., Coskun, D., De Kok, L.J., Lambers, H., Schjoerring, J.K., & White, P.J. (2023). Functions of macronutrients. In *Marschner's mineral nutrition of plants* (pp. 201-281): Elsevier. https://doi.org/10.1016/B978-0-12-819773-8.00019-8

Ishfaq, M., Kiran, A., Rehman, H.U., Farooq, M., Ijaz, N.H., Nadeem, F., Azeem, I., Li, X., & Wakeel, A. (2022). Foliar nutrition: Potential and challenges under multifaceted agriculture. *Environmental and Experimental Botany*, *200*, 104909. https://doi.org/10.1016/j.envexpbot.2022.104909

Jamal, Z., Hamayun, M., Ahmad, N., & Chaudhary, M. (2006). Effect of soil and foliar application of different concentrations of NPK and foliar application of (NH4) 2SO4 on different parameters in wheat. *Journal of Agronomy, 5*(2), 251-256. https://scialert.net/abstract/?doi=ja.2006.251.256

Januszkiewicz, R., Kulczycki, G., Sacała, E., & Kabała, C. (2025). Effect of nutrient forms in foliar fertilizers on the growth and biofortification of maize on different soil types. *Agronomy*, *15*(6), 1482. https://doi.org/10.3390/agronomy15061482

Khasawneh, A.E.-R., Alsmairat, N., Othman, Y.A., Ayad, J.Y., Al-Hajaj, H., & Qrunfleh, I.M. (2022). Controlled-release nitrogen fertilizers for improving yield and fruit quality of young apricot trees. *Scientia Horticulturae, 303*, 111233. https://doi.org/10.1016/j.scienta.2022.111233

Kirkby, E.A. (2023). Introduction, definition, and classification of nutrients. In *Marschner's mineral nutrition of plants* (pp. 3-9): Elsevier. https://doi.org/10.1016/B978-0-12-819773-8.00016-2

Mahajan, G.R., Das, B., Murgaokar, D., Herrmann, I., Berger, K., Sahoo, R.N., & Kulkarni, R.M. (2021). Monitoring the foliar nutrients status of mango using spectroscopy-based spectral indices and PLSR-combined machine learning models. *Remote Sensing, 13*(4), 641. https://doi.org/10.1016/B978-0-12-819773-8.00016-2

Masson, P., Dalix, T., & Bussière, S. (2010). Determination of major and trace elements in plant samples by inductively coupled plasma–mass spectrometry. *Communications in Soil Science and Plant Analysis, 41*(3), 231-243. https://doi.org/10.1080/00103620903460757

Nasar, J., Wang, G., Ahmad, S., Muhammad, I., Zeeshan, M., Gitari, H., Adnan, M., Fahad, S., Khalid, M.H.B., Zhou, X., Abdelsalam, N.R., Ahmed, G.A., & Hasan, M.E. (2022). Nitrogen fertilization coupled with iron foliar application improves the photosynthetic characteristics, photosynthetic nitrogen use efficiency, and the related enzymes of maize crops under different planting patterns. *Frontiers in Plant Science, 13*. https:// doi: 10.3389/fpls.2022.988055

Obeidat, W., Avila, L., Earl, H., & Lukens, L. (2018). Leaf spectral reflectance of maize seedlings and its relationship to cold tolerance. *Crop Science, 58*(6), 2569-2580. https://doi.org/10.2135/cropsci2018.02.0115

Okyere, F.G., Cudjoe, D., Sadeghi-Tehran, P., Virlet, N., Riche, A.B., Castle, M., & Mohareb, F. (2023). Modeling the spatial-spectral characteristics of plants for nutrient status identification using hyperspectral data and deep learning methods. *Frontiers in Plant Science, 14*, 1209500. https://doi.org/10.3389/fpls.2023.1209500

Othman, Y., Steele, C., VanLeeuwen, D., & Hilaire, R.S. (2015). Hyperspectral surface reflectance data detect low moisture status of Pecan Orchards during flood irrigation. *Journal of the American Society for Horticultural Science, 140*(5), 449-458. https://doi.org/10.21273/jashs.140.5.449

Othman, Y.A., & Al-Zaben, N.M. (2025). Effect of fertiliser application method and nutrient solution pH on growth, yield and flower quality of gardenia (Gardenia jasminoides). *New Zealand Journal of Crop and Horticultural Science*, 1-15. https://doi.org/10.1080/01140671.2025.2502117

Othman, Y.A., & Leskovar, D. (2024). Leaf orientation method as a proxy for sensing nitrogen and water deficit in tomato plants. *HortScience, 59*(12), 1740-1748. https://doi.org/10.21273/hortsci18176-24

Pandey, P., Veazie, P., Whipker, B., & Young, S. (2023). Predicting foliar nutrient concentrations and nutrient deficiencies of hydroponic lettuce using hyperspectral imaging. *Biosystems Engineering, 230*, 458-469. https://doi.org/10.1016/j.biosystemseng.2023.05.005

Peñuelas, J., Gamon, J., Fredeen, A., Merino, J., & Field, C. (1994). Reflectance indices associated with physiological changes in nitrogen-and water-limited sunflower leaves. *Remote Sensing of Environment, 48*(2), 135-146. https://doi.org/10.1016/0034-4257(94)90136-8

Qarallah, B., Othman, Y.A., Al-Ajlouni, M., Alheyari, H.A., & Qoqazeh, B.A.A. (2022). Assessment of small-extent forest fires in semi-arid environment in Jordan using Sentinel-2 and Landsat sensors data. *Forests, 14*(1), 41. https://doi.org/10.3390/f14010041

Shalaby, O.A. (2024). Using *Bacillus megaterium* as a bio-fertilizer alleviates salt stress, improves phosphorus nutrition, and increases cauliflower yield. *Journal of Plant Nutrition, 47*(6), 926-939. https://doi.org/10.1080/01904167.2023.2291022

Shalaby, O.A., & Ramadan, M.E.-S. (2024). Mycorrhizal colonization and calcium spraying modulate physiological and antioxidant responses to improve pepper growth and yield under salinity stress. *Rhizosphere, 29*, 100852. https://doi.org/10.1016/j.rhisph.2024.100852

Siedliska, A., Baranowski, P., Pastuszka-Woźniak, J., Zubik, M., & Krzyszczak, J. (2021). Identification of plant leaf phosphorus content at different growth stages based on hyperspectral reflectance. *BMC Plant Biology, 21*(1), 28. https://doi.org/10.1186/s12870-020-02807-4

Singh, L., Mutanga, O., Mafongoya, P., Peerbhay, K., & Crous, J. (2022). Hyperspectral remote sensing for foliar nutrient detection in forestry: A near-infrared perspective. *Remote Sensing Applications: Society and Environment, 25*, 100676. https://doi.org/10.1016/j.rsase.2021.100676

Sokolowski, A.C., Barrios, M.B., Wolski, J.E., Mónaco Henke, J.M., Rodríguez, H.A., Navas, M., Grazia, J.D., & Prack McCormick, B. (2025). Impact of fertilization and crop type on horticultural soil quality: A 3-year, open-field experiment. *Soil Use and Management, 41*(1), e70007. https://doi.org/10.1111/sum.70007

Van Acker, T., Theiner, S., Bolea-Fernandez, E., Vanhaecke, F., & Koellensperger, G. (2023). Inductively coupled plasma mass spectrometry. *Nature Reviews Methods Primers, 3*(1), 52. https://doi.org/10.1038/s43586-023-00235-w

Youssef, S.M., El-Serafy, R.S., Ghanem, K.Z., Elhakem, A., & Abdel Aal, A.A. (2022). Foliar spray or soil drench: Microalgae application impacts on soil microbiology, morpho-physiological and biochemical responses, oil and fatty acid profiles of chia plants under alkaline stress. *Biology, 11*(12), 1844. https://doi.org/10.3390/biology11121844

Wu, J., Poh, Z. Y., Patil, A.C., Park, B., Volpe, G., & Urano, D. (2025). Analysis of plant nutrient deficiencies using Multi-Spectral imaging and optimized segmentation model. *rXiv preprint arXiv:2507.14013*. https://doi.org/10.48550/arXiv.2507.14013

Zahir, S.A.D.M., Jamlos, M.F., Omar, A.F., Jamlos, M.A., Mamat, R., Muncan, J., & Tsenkova, R. (2024). Review–Plant nutritional status analysis employing the visible and near-infrared spectroscopy spectral sensor. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 304*, 123273. https://doi.org/10.1016/j.saa.2023.123273