



Sensor-Based Assessment of Cowpea Responses to Various Fertilizer Treatments Using Optical and Thermal Imaging Techniques

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Abstract

This study aimed to evaluate the responses of cowpea (*Vigna unguiculata* L.) to various fertilizer treatments and to determine the applicability of sensor-based measurements including SPAD, Normalized Difference Vegetation Index (NDVI), and thermal imaging in monitoring fertilizer efficiency. The experiment was conducted in the research greenhouse of Harran University Faculty of Agriculture using a Completely Randomized Design (CRD) with five treatments and three replications. Urea application resulted in the highest physiological improvement, increasing chlorophyll content (SPAD +25%), canopy vigor (NDVI +18%), and plant height (+22%), and produced the greatest biomass accumulation (fresh weight: 5.8 g plant⁻¹; dry weight; 1.8 g plant⁻¹). Microbial fertilizer moderately enhanced chlorophyll content (SPAD +12%) and canopy vigor (NDVI +10%). Iron treatment increased plant moisture content to 86% while reducing dry matter percentage to 27%, indicating its distinct influence on water-use dynamics. Thermal imaging showed that canopy temperatures reached ~42 °C in the control, whereas urea and microbial treatments maintained lower temperatures (35–37 °C), reflecting improved transpiration and reduced heat stress. Correlation analysis revealed strong positive associations between biomass (fresh and dry weight) and SPAD and NDVI values ($r=0.82-0.89$; $p<0.01$). Principal component analysis (PCA) explained 74.6% of the total variation in physiological (SPAD, NDVI, canopy temperature), morphological (plant height), and harvest-related traits, clearly separating the urea treatment along the biomass–photosynthetic activity axis. Overall, urea proved to be the most effective fertilization strategy for improving physiological performance and biomass production in cowpea; microbial fertilizers provided a sustainable alternative; and iron played a decisive role in plant water relations. Furthermore, sensor-based parameters (SPAD, NDVI, thermal imaging) were demonstrated to be reliable tools for monitoring fertilizer efficiency and supporting early yield prediction.

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1. Introduction

Cowpea (*Vigna unguiculata* L.) is one of the most important legumes cultivated in tropical and subtropical regions and is considered a strategic crop, particularly in semi-arid areas, due to its high adaptability and nutritional value. With an annual global production of approximately 5.4 million tons, cowpea serves as a vital source of protein (23.4%), carbohydrates (55–66%), and minerals, making it essential for both human nutrition and livestock feed (Souza et al., 2025). However, low soil fertility, nutrient deficiencies, drought, and salinity are major environmental stress factors that limit its growth and yield potential (Jat et al., 2025). Among the key strategies to enhance crop productivity, balanced and efficient fertilization plays a critical role. Nitrogen, in particular, is fundamental for increasing photosynthetic capacity and biomass accumulation. For instance, Wang et al. (2025) demonstrated that nitrogen application in maize improved dry matter accumulation and grain yield while enhancing nitrogen use efficiency. Similarly, Obour et al. (2025) reported that NPK fertilization in cowpea under Senegalese conditions increased grain yield by 22–40% and improved its economic value. Among micronutrients, zinc (Zn) and iron (Fe) are essential for physiological processes such as photosynthetic pigment synthesis, enzyme activation, and water balance; their deficiencies lead to chlorophyll degradation, reduced photosynthetic capacity, and growth retardation (Hou et al., 2025). Moreover, microbial fertilizers (PGPR, mycorrhizal inoculants, and biocontrol agents) facilitate nutrient uptake and contribute to physiological and morphological development (Özaktan et al., 2025). In recent years, the use of optical and thermal sensors to evaluate fertilizer efficiency has become increasingly widespread. SPAD chlorophyll meters provide reliable information on plant nitrogen status by quantifying leaf chlorophyll content, whereas the Normalized Difference Vegetation Index (NDVI) shows strong correlations with photosynthetic activity and leaf area index (Shivashankar et al., 2025). Thermal imaging,

on the other hand, measures leaf temperature and provides indirect insights into plant water use, transpiration capacity, and stress tolerance (Souza et al., 2025). Furthermore, the integration of SPAD and NDVI data with multispectral and hyperspectral imaging techniques has enabled the development of highly accurate yield prediction models across various field crops (Li et al., 2025; Rufaioğlu et al., 2025). Although existing literature highlights the strong effects of nitrogen fertilization on crop growth and yield, as well as the predictive capacity of sensor-based parameters, studies that comprehensively evaluate the effects of mineral (Fe, Zn), urea, and microbial fertilizers on the physiological, morphological, and yield parameters of cowpea using modern sensor-based approaches remain limited. In this context, the present study aims to investigate the effects of different fertilizer applications (urea, Fe, Zn, and microbial fertilizers) on the physiological and morphological development and post-harvest traits of cowpea, employing sensor-based measurements such as SPAD, NDVI, and thermal imaging, and to elucidate the relationships among these parameters using multivariate statistical approaches.

2. Material and Methods

2.1. Experimental design and plant material

The experiment was initiated on May 1, 2025, with the sowing of cowpea (*Vigna unguiculata* L.) seeds under semi-controlled greenhouse conditions and was completed on July 3, 2025. The greenhouse environment was highly homogeneous in terms of temperature, relative humidity, and light, and therefore the pots were arranged according to a Completely Randomized Design (CRD) with five fertilizer treatments and three replications, totaling 15 pots. Seeds were sown into 1 L pots, each filled with air-dried, sieved field soil. Five seeds were sown per pot, and after emergence, plants were thinned to maintain one healthy plant per pot, ensuring equal plant density. The soil used in the experiment was a clay-loam (19.20% sand, 30.10% silt, 50.70% clay) with a slightly alkaline pH (7.61) and low

salinity (EC 0.79 dS m⁻¹). It contained 10.16% lime, 0.78% organic matter, and 0.35% total nitrogen. Available nutrients included 170.10 mg kg⁻¹ K, 4.13 mg kg⁻¹ P, and 295.60 mg kg⁻¹ Mg, along with Fe (2.95 mg kg⁻¹), Cu (0.82 mg kg⁻¹) and Mn (0.39 mg kg⁻¹). At sowing, diammonium phosphate (DAP, 18-46-0) was applied to all pots. The field-recommended rate (8 kg P₂O₅ da⁻¹) was converted to pot scale

based on soil volume, corresponding to 48 mg DAP kg⁻¹ of soil. Throughout the experiment, no insect or disease pressure was observed; therefore, no chemical pest control was applied. Irrigation was applied uniformly across all treatments. Foliar fertilizers were applied once, at the six- to eight-leaf growth stage (V6–V8).

Table 1. Description of treatments and rates

Treatment	Abbreviation	Content	Fertilizer Dose	Exact doses for pot
Control				
Urea	Urea	Urea (46% N)	10 kg da ⁻¹	10 g L ⁻¹
Zinc sulphate	Zn	Zinc (ZnSO ₄ ·7H ₂ O, 22% Zn)	2,5 kg da ⁻¹	3 g L ⁻¹
Microbial (Hızır ST1140)	Microbial	<i>Clonostachys rosea</i> st1140	1 L da ⁻¹	2 mL L ⁻¹
Ferrous sulphate heptahydrate	Fe	Ferrous (FeSO ₄ ·7H ₂ O, 20,1% Fe)	1 L da ⁻¹	2 mL L ⁻¹

2.2. Morphological parameters

Plant height (cm) was recorded at 6, 14, 20, and 26 days after emergence (DAO) using the conventional method, whereby the distance from the soil surface to the apical point of the main stem was measured with a ruler (Mfeka et al., 2019). For each pot, three independent measurements were taken for all parameters, each from different orientations or representative points of the plant. Accordingly, each parameter was represented by a total of 45 observations (5 treatments × 3 replications × 3 measurements), ensuring adequate measurement reliability and reducing within-pot variation.

2.3. Post harvest parameters

The aboveground parts of each plant were harvested, and fresh biomass (fresh weight, FW) was measured using a high-precision electronic balance. Subsequently, the same samples were dried in a ventilated oven (Nüve FN 500, Ankara, Türkiye) at 65 °C for 48 h until constant weight was achieved, after which dry weight (DW) values were recorded. Following drying, moisture content (MC, %) was calculated as the ratio of the difference between FW and DW to FW; dry matter content (DMC, %) was determined as the ratio of DW to FW; the water-to-dry matter ratio (H₂O/DM) was calculated as the ratio of water

content to dry matter; and water content (WC) was expressed as the absolute difference between FW and DW. These calculations were based on standard methodologies for biomass determination through fresh and dry weight measurements (Turnage, 2022; Xu and Zhou, 2011; Yan et al., 2023).

2.4. Optic sensor measurements

Physiological observations were conducted at weekly intervals, and all measurements were carefully performed on the same day. All measurements were carried out consecutively between 13:00 and 15:00 to minimize diurnal variation. Measurements were based on three replications, and the mean values obtained from each replication were used for statistical analyses. Leaf chlorophyll content was determined using a Konica Minolta SPAD-502 Plus chlorophyll meter (Konica Minolta Inc., Osaka, Japan). SPAD measurements rely on the difference in light absorption between the red (650 nm) and near-infrared (940 nm) regions, indirectly reflecting leaf chlorophyll concentration. For each plant, measurements were taken from three leaves located in the middle canopy, and their mean values were considered for analysis (Yuan et al., 2016). Measurements were taken from three fully expanded leaves, specifically the third leaf from the apex. Normalized Difference Vegetation index (NDVI) measurements were

performed with a Trimble GreenSeeker Handheld Crop Sensor (Trimble Inc., Sunnyvale, CA, USA). The GreenSeeker calculates NDVI based on the ratio of reflected red (656 nm) and near-infrared (774 nm) wavelengths, thereby enabling the assessment of plant biomass, photosynthetic capacity, and stress status (Raun et al., 2011). NDVI measurements were taken at a fixed distance approximately 70 cm above the vegetation cover of each pot.

2.5. Thermal image processing

Thermal imaging analyses were performed using an infrared thermal camera, FLIR T540 (FLIR Systems Inc., Wilsonville, USA). Owing to its high resolution (464×348 pixels) and thermal sensitivity of 0.03°C , the device enabled reliable detection of small temperature differences. Images were acquired for each treatment with three replications and analyzed using FLIR Tools software (v6.4). Leaf and canopy temperatures of the plants were determined, and visual evaluations were carried out based on color scale mapping. This method is widely applied to investigate plant–water relations and stress responses (Yang et al., 2025; Costa et al., 2025).

2.6. Statistical analysis and data visualization

The data were analyzed based on a Completely Randomized Design (CRD). The fundamental assumptions of ANOVA, namely normality (Shapiro–Wilk test) and homogeneity of variances (Levene's test), were verified and found to be satisfied. A one-way ANOVA model was employed to determine differences among treatments, and when significant effects were detected (95% confidence level, $p < 0.05$), means were separated using Tukey's HSD test (Gomez and Gomez, 1984). Statistical analyses were performed using JMP Pro 17 software, while data visualizations were conducted in Python 3.10 (pandas, matplotlib, seaborn, scipy). Line graphs with error bars were used for temporal data, bar charts for post-harvest biomass measurements, and correlation heatmaps to

explore relationships among variables. Principal component analysis (PCA) was performed to integrate physiological, thermal, and biomass-related variables, to identify multivariate patterns generated by the fertilizer treatments, and to reveal the separation among treatment groups.

3. Findings

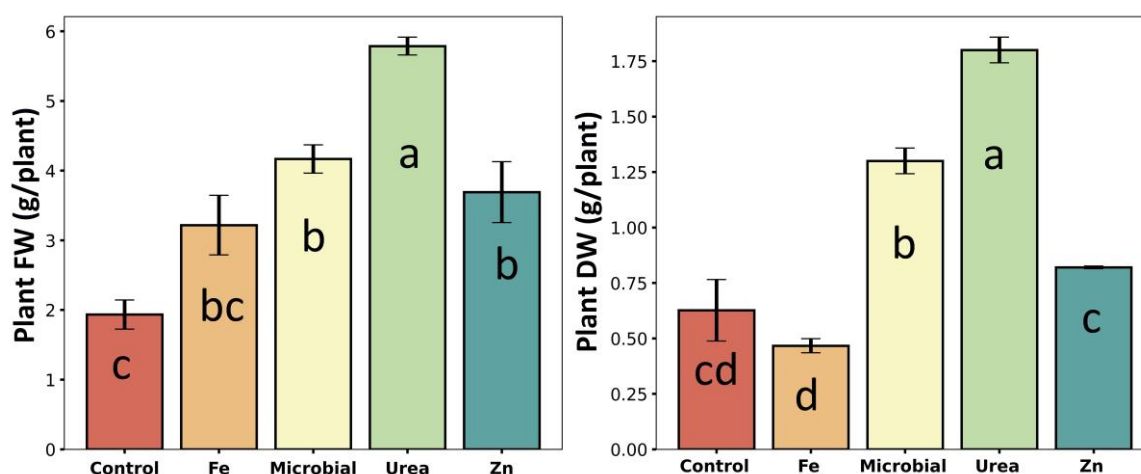
3.1. Descriptive statistical analyses

Plant height showed statistically significant differences ($p < 0.01$) at 6 and 26 DAO. SPAD measurements were found to be highly significant ($p < 0.01$) at all observation periods indicating that foliar fertilizer applications had a pronounced effect on chlorophyll content. NDVI values showed significant variation at 6, 14, and 20 days ($p < 0.05$; $p < 0.01$), demonstrating that the treatments influenced canopy density and photosynthetic activity. Plant temperature measurements were significant only at day 6 ($p < 0.05$) but were statistically non-significant at later stages. Fresh weight ($p < 0.01$) and dry weight ($p < 0.01$) showed highly significant differences among treatments. Moreover, WC, DMC, and the $\text{H}_2\text{O}/\text{DM}$ ratio were significantly affected, while MC differed at the 5% significance level. These findings highlight that foliar fertilizer applications exert strong effects particularly on chlorophyll content, vegetative growth, and biomass formation (Table 2). Analysis of post-harvest biomass parameters revealed significant differences among fertilizer treatments ($p < 0.01$). The highest FW values were obtained from the urea treatment (approximately 5.8 g plant^{-1}). Microbial and zinc treatments resulted in moderate fresh weight values, whereas the control and Fe treatments exhibited lower biomass. Similarly, for DW, the urea application resulted in the highest value (approximately 1.8 g plant^{-1}). The microbial fertilizer treatment ranked second, while zinc, control, and Fe applications were grouped in lower classes (Figure 1).

Table 2. F-values from the analysis of variance (ANOVA) for the effects of different fertilizer applications on physiological parameters (6, 14, and 20 days after emergence, DAO), morphological traits, and post-harvest parameters in cowpea (*Vigna unguiculata* L.).

Parameters	DAO (F Value)			
	6	14	20	26
Plant Height (cm)	18,84**	22,42	71,29	60,66**
SPAD	11,50**	21,56**	15,30**	
NDVI	4,23*	5,52*	8,43**	
Plant Temperature (°C)	3,99*	1,56	1,46	
Post Harvest (F Value)				
Plant Fresh Weight (g)			20,81**	
Plant Dry Weight (g)			55,07**	
WC			9,42**	
MC (%)			4,41*	
DMC (%)			4,41*	
H ₂ O/DM			5,41**	

*, **, P≤0.05 and P≤0.01 significant level, respectively. ns; non-significant Levels not connected by same letter are significantly different

**Figure 1.** Effects of different fertilizer applications on cowpea: FW, g plant⁻¹ and DW, g plant⁻¹. Error bars represent standard error. Means sharing the same letter are not statistically different according to Tukey's HSD test (p < 0.05)

The effects of different fertilizer applications on physiological parameters of cowpea varied over time. Regarding SPAD values, urea treatment consistently resulted in the highest chlorophyll content across all observation periods and was found to be highly significant (p<0.01). Microbial and zinc treatments produced intermediate values, whereas the control and Fe treatments exhibited lower SPAD levels. For NDVI, urea application peaked at DAO 14, indicating the highest photosynthetic activity (p<0.01). Zinc and microbial fertilizer treatments ranked in the second group, while the control treatment showed the lowest NDVI values. These results demonstrate that urea application exerted a strong influence on canopy density and leaf

development. In terms of canopy temperature, differences among treatments were limited, with significance detected only at DAO 6 (p<0.05). The control group exhibited higher temperature values compared to the other treatments, which may be attributed to insufficient evaporative cooling due to reduced leaf cover (Figure 2). PH measurements showed a continuous increase throughout the experimental period. The highest plant height was recorded under urea treatment, reaching approximately 32 cm at day 26 and found to be statistically significant. Microbial and zinc treatments promoted moderate growth, while Fe application remained at lower levels. The control group consistently exhibited the shortest plant height across all periods. These

findings highlight that urea application is the most effective foliar fertilization strategy for

promoting vegetative growth in cowpea (Figure 2).

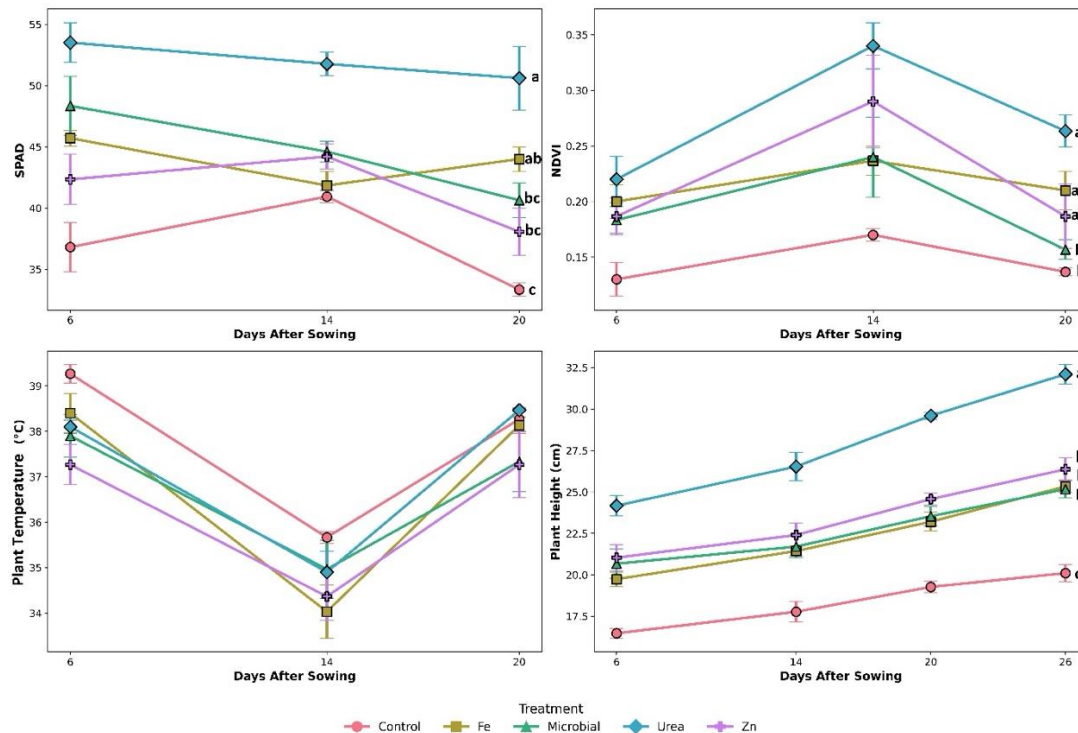


Figure 2. Effects of different fertilizer applications on SPAD values, NDVI, canopy temperature (°C), and plant height (cm plant⁻¹) in cowpea. Measurements were conducted at different days after emergence (DAO 6, 14, and 20). Error bars represent standard error. Means sharing the same letter, or means without any letter, are not statistically different according to Tukey's HSD test ($p < 0.05$)

The effects of different fertilizer applications on leaf temperature in cowpea were further supported by thermal imaging. At DAO 6, control plants exhibited higher temperature values (~39–43 °C), indicating limited evaporative cooling due to insufficient leaf development and transpiration. In contrast, plants treated with urea and microbial fertilizer displayed lower leaf temperatures, suggesting more efficient water use and enhanced photosynthetic activity. At DAO 14, leaf temperatures across all treatments ranged between 35–40 °C, with urea and zinc treatments standing out for maintaining relatively lower temperatures. During this period, improved leaf development, increased

photosynthetic activity, and enhanced transpiration likely contributed to reduced canopy temperatures. At DAO 20, control plants again recorded the highest temperatures (~42–44 °C), whereas urea-treated plants exhibited the lowest temperature levels. This finding indicates that urea application not only promotes growth parameters but also exerts a beneficial effect on plant water balance and thermal regulation. Overall, differences in leaf temperature observed through thermal imaging were consistent with morphological growth patterns, highlighting that particularly urea and microbial fertilizers enhanced vegetative development and physiological resilience (Figure 3).

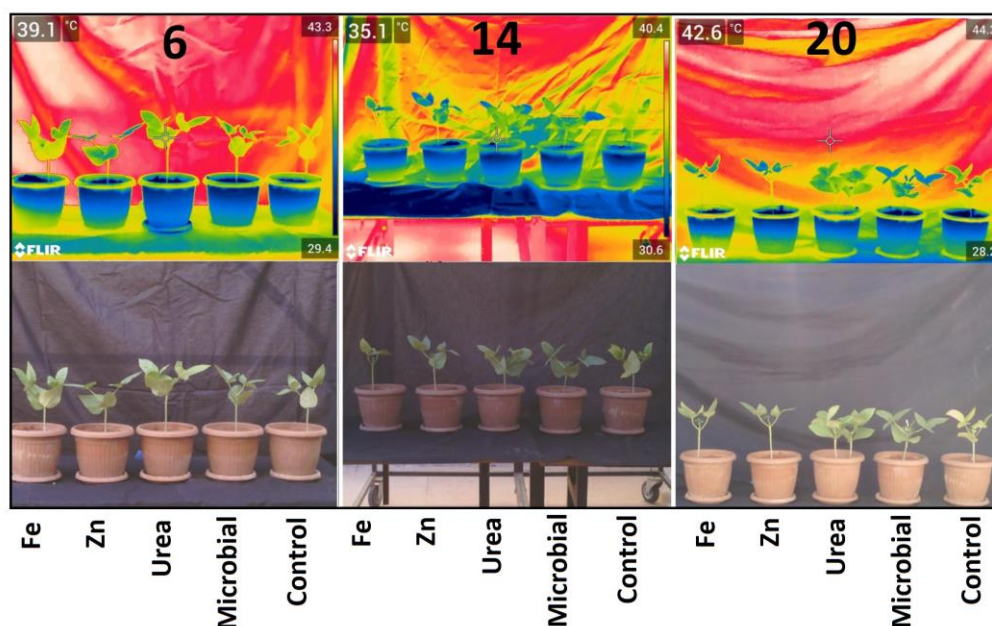


Figure 3. Thermal images (top row) and visual photographs (bottom row) of cowpea plants under different fertilizer treatments at 6, 14, and 20 days after emergence (DAO). In thermal images, red–orange areas represent higher temperatures, while blue–green areas indicate lower temperatures

Analysis of post-harvest quality parameters revealed significant differences among treatments. MC was found to be the highest under Fe treatment, exceeding 85%, and was statistically significant ($p < 0.05$). In contrast, the control group exhibited lower MC values, while microbial, urea, and Zn applications produced intermediate results. In terms of WC, the urea treatment recorded the highest value (~ 4.0) and was highly significant ($p < 0.01$), whereas the control group showed the lowest value. This finding indicates that urea application enhanced the water retention

capacity of cowpea plants. For DMC, the highest value was observed in control treatment ($\sim 33\%$) and was significant, while the Fe treatment yielded the lowest DMC. Microbial, urea, and Zn treatments were classified into the intermediate group. Regarding the H_2O/DM ratio, Fe application exhibited the highest value (~ 6.0) and was statistically significant ($p < 0.01$). The control, microbial, and urea treatments displayed lower ratios, while Zn treatment produced an intermediate value between these groups (Figure 4).

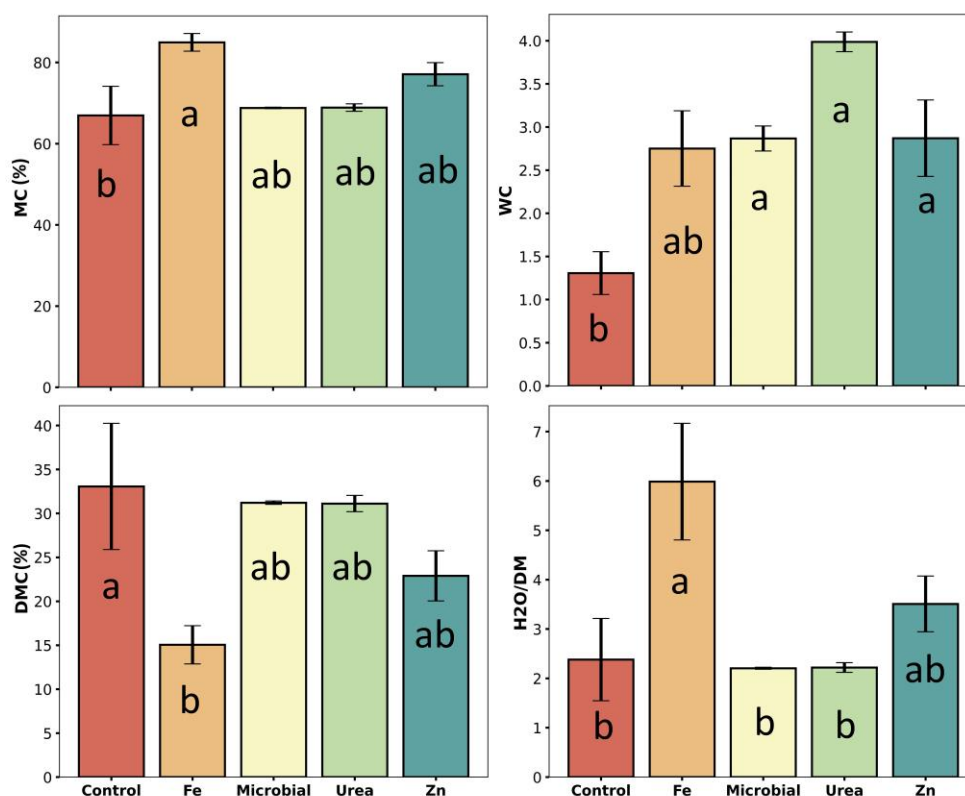


Figure 4. Effects of different fertilizer applications on post-harvest quality parameters of cowpea: MC, %, WC, DMC, %, and H₂O/DM. Error bars represent standard error. Means sharing the same letter are not statistically different according to Tukey's HSD test ($p < 0.05$)

The radar diagram demonstrates the integrated effects of different fertilizer applications on cowpea physiological, morphological, and post-harvest traits. Urea treatment consistently outperformed all other treatments, covering the widest area on the radar plot and showing particularly high performance in SPAD, NDVI, plant height, fresh and dry biomass, and WC. Microbial fertilizer exhibited an intermediate performance, with higher NDVI, SPAD, and

DW values compared to the control group. Zinc application yielded favorable outcomes in specific parameters (SPAD-14, NDVI-14, PH-20), although its overall effect remained limited compared to urea. Iron application was distinguished by its effects on MC and H₂O/DM ratio; however, it showed lower performance in dry matter accumulation and biomass production. The control treatment exhibited the lowest value across all parameters (Figure 5).

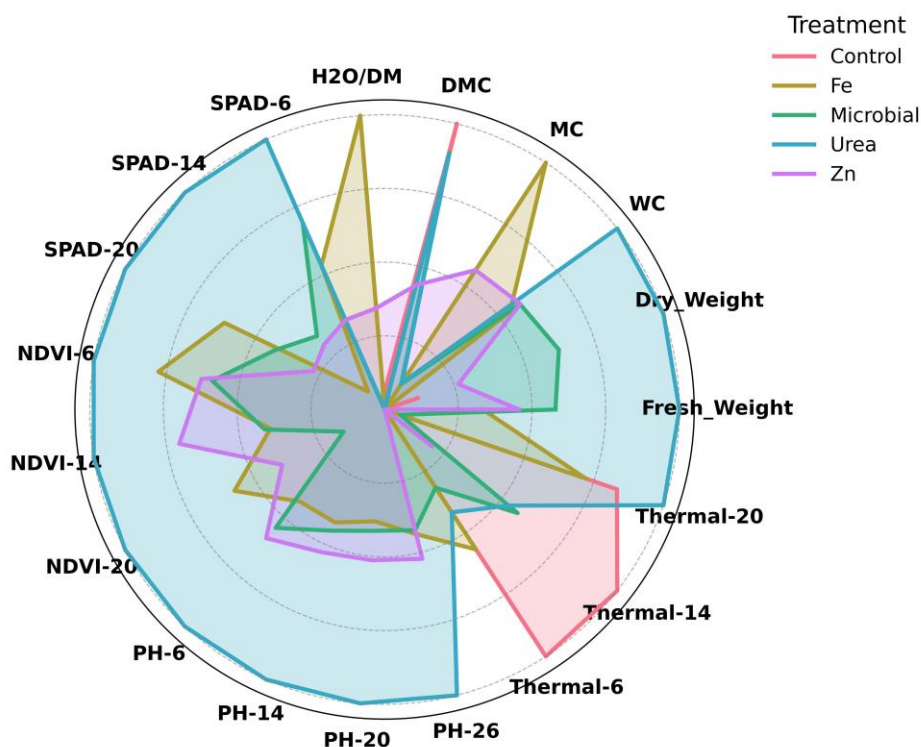


Figure 5. Radar diagram illustrates the overall effects of different fertilizer applications on physiological, morphological, and post-harvest parameters in cowpea

Correlation analysis revealed strong interrelationships among physiological, morphological, and post-harvest parameters in cowpea. A strong and highly significant positive correlation was observed between FW and DW ($r > 0.80$, $p < 0.001$). Both FW and DW were also strongly correlated with SPAD values, NDVI, and PH. This finding highlights the reliability of sensor-based parameters as predictors of biomass. A strong negative correlation was detected between MC and DMC ($r < -0.70$, $p < 0.001$). Similarly, the

H₂O/DM ratio was inversely related to DMC, indicating that high water retention capacity may limit dry matter accumulation. Thermal measurements (Thermal-6, -14, -20) showed negative correlations with SPAD, NDVI, and PH, suggesting that increased leaf temperature had adverse effects on photosynthetic capacity and growth. Notably, Thermal-20 exhibited statistically significant inverse correlations with SPAD-20 and NDVI-20 ($p < 0.01$) (Figure 6).

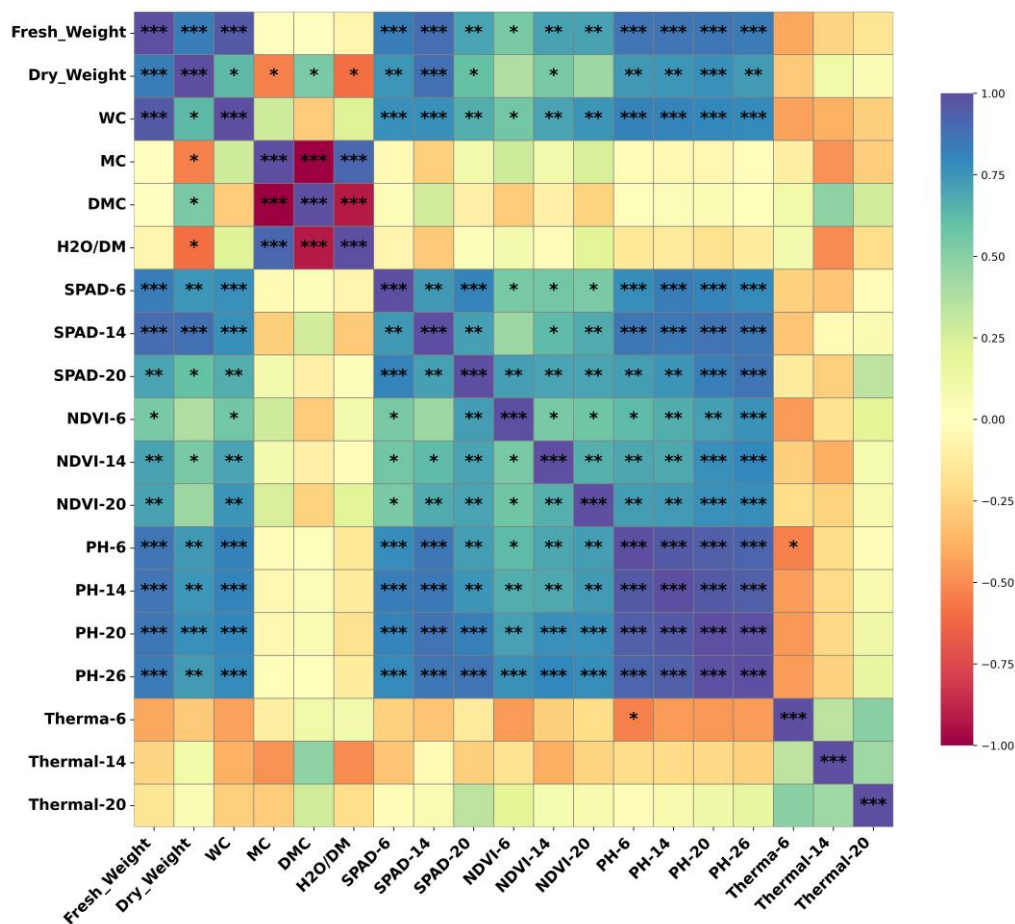


Figure 6. Correlation matrix among physiological, morphological, and post-harvest parameters in cowpea. The color scale represents correlation coefficients ranging from -1 to $+1$, with positive correlations shown in blue and negative correlations in red. *, **, $P \leq 0.05$ and $P \leq 0.01$ significant level, respectively. ns; non-significant. Levels not connected by same letter are significantly different

PCA proved to be a powerful tool in distinguishing the effects of different fertilizer applications on cowpea physiological, morphological, and post-harvest traits. The first two components explained 74.6% of the total multivariate variance ($PC1=54.0\%$; $PC2=20.6\%$), capturing the combined variability of all measured parameters, including SPAD and NDVI values, plant height at different growth stages, canopy temperature profiles, and biomass- and moisture-related yield components. In the biplot, urea treatment was clearly separated from the other treatments and showed strong associations with SPAD, NDVI, PH, and biomass parameters. This indicates that urea was the most effective treatment in supporting vegetative growth and photosynthetic

capacity. The microbial treatment exhibited a moderate separation, primarily associated with SPAD and NDVI values. Zn treatment clustered close to microbial fertilizer, whereas Fe treatment showed a strong association with MC and the H_2O/DM ratio. The control group formed a distinct cluster on the PCA plane, being linked to low-performing parameters (Figure 7). Examination of variable contribution plots revealed that FW, DW, SPAD, NDVI, and PH contributed most strongly to $PC1$, whereas $PC2$ was primarily shaped by MC, H_2O/DM , and thermal parameters. This pattern indicates that $PC1$ represents growth and photosynthetic capacity, while $PC2$ reflects water relations and stress-related parameters (Figure 7).

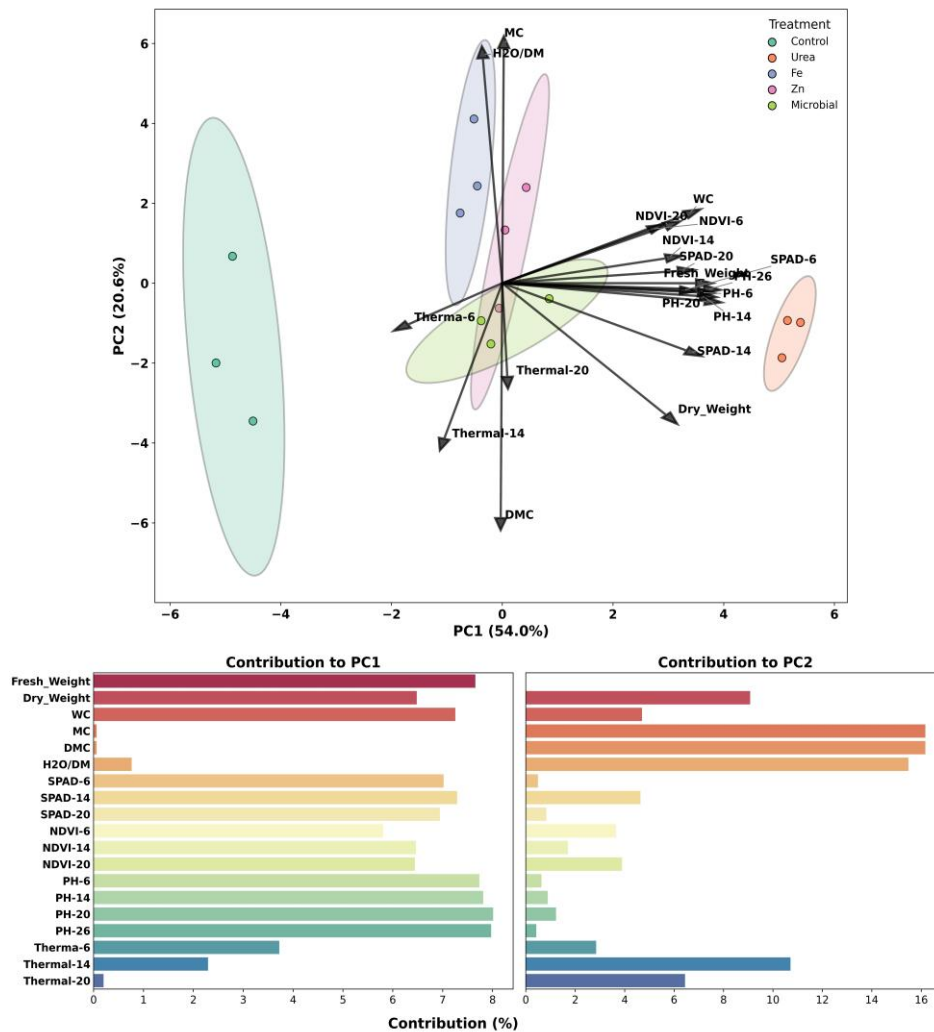


Figure 7. Principal component analysis (PCA) biplot illustrating the effects of different fertilizer applications on physiological, morphological, and post-harvest parameters in cowpea (upper panel), and variable contributions to PC1 and PC2 (lower panels)

4. Discussion

4.1. Effects of fertilizer applications on physiological and yield parameters

In this study, distinct physiological and biomass responses were observed among the fertilizer treatments, highlighting the central role of nutrient-specific metabolic pathways in shaping cowpea performance. Urea application produced the strongest enhancement in SPAD, NDVI, plant height, and biomass accumulation. This response is biologically expected, as nitrogen is the primary driver of chlorophyll biosynthesis and photosynthetic metabolism. As the structural component of chlorophyll molecules and the principal element in Rubisco and other photosynthetic

enzymes, nitrogen directly enhances CO₂ assimilation, leaf area expansion, and stomatal conductance (Hawkesford, 2017; Kant et al., 2011). The substantial increases in SPAD and NDVI recorded under urea fertilization in this study therefore align with the well-established role of nitrogen in improving canopy photosynthetic efficiency and vegetative growth. Similar trends have been documented in maize and cowpea, where nitrogen fertilization significantly increased dry matter accumulation, grain yield, and nitrogen use efficiency (Wang et al., 2025; Obour et al., 2025). Microbial fertilizer application resulted in moderate yet meaningful improvements in SPAD and NDVI, indicating enhanced physiological functioning despite lower

magnitude compared with urea. These effects can be attributed to microbial contributions to rhizosphere activity, including the production of phytohormones such as indole-3-acetic acid (IAA) and cytokinins, stimulation of root proliferation, solubilization of nutrients, and improved tolerance to environmental stress (Özaktan et al., 2025). As reported by Bagsao and Rocha (2025), organic and microbial fertilizers can deliver comparable physiological outcomes to inorganic fertilization, particularly in legume systems where biological processes in the root zone strongly influence nutrient uptake and photosynthetic vigor. Fe and Zn applications induced more limited changes in chlorophyll synthesis and growth parameters, suggesting that these micronutrients function more effectively when supplied as part of a balanced fertilization regime rather than individually. The physiological patterns observed in the Fe treatment namely increased water content but reduced dry matter accumulation may reflect the dual role of Fe in plant metabolism. While Fe is essential for chlorophyll formation and electron transport chains, excessive or imbalanced Fe availability can stimulate the production of reactive oxygen species (ROS), compromise membrane integrity, and trigger osmotic stress responses, leading to water retention in tissues but constrained carbon assimilation and biomass accumulation (Ravet and Pilon., 2013). Furthermore, Fe and Zn imbalances are known to reduce PSII photochemical efficiency and limit biomass development, which is consistent with the relatively weak responses recorded in this study (Roosta et al., 2018). Similarly, although Zn supports numerous physiological functions including enzyme activation, protein synthesis, membrane stability, and antioxidant defense, its isolated application is often insufficient to induce major improvements in biomass unless supported by adequate macronutrient availability (Dehnavi and Sheshbahre, 2017). Thermal imaging results provided additional physiological insights into how fertilizer applications influenced plant water-use dynamics and stress status. The lower canopy temperatures recorded under urea and

microbial treatments indicate higher transpiration efficiency and functional stomatal activity, whereas the elevated temperatures in control plants suggest reduced cooling capacity and greater susceptibility to stress. These findings are in agreement with Souza et al. (2025), who reported that thermal imaging serves as an effective early indicator of plant water stress and that microbial inputs may enhance stomatal conductance and water-use efficiency. Taken together, the overall results demonstrate that urea fertilization is the most effective strategy for improving chlorophyll content, canopy vigor, and biomass accumulation in cowpea. Microbial fertilizers provide a sustainable and supportive alternative by enhancing root–soil interactions and physiological functioning, whereas Fe and Zn act as complementary nutrients with more specific roles in chlorophyll metabolism, water relations, and enzymatic processes. These mechanistic insights highlight the importance of integrating both macronutrient and micronutrient management in cowpea cultivation and underscore the potential of combining optical and thermal sensing tools to better understand nutrient-mediated physiological responses.

4.2. Fertilization strategies and the role of thermal imaging in water relations

The Fe treatment was characterized by high MC and H₂O/DM ratio; however, when considered alongside its low dry matter content DMC, it became evident that this treatment enhanced water retention while limiting biomass accumulation. Similar findings were reported by Jat et al. (2025), who observed that phosphorus application under salinity conditions improved water relations but excessive ion accumulation constrained biomass development. In contrast, urea treatment was distinguished by the highest WC, and when evaluated together with increased biomass, this suggests that nitrogen improved water use efficiency. Supporting this, Obour et al. (2025) reported that NPK fertilization in cowpea under Senegalese conditions not only increased yield but also improved water use efficiency, corroborating

the positive role of urea in water relations. Our thermal imaging results revealed higher leaf temperatures in the control group, whereas urea and microbial treatments maintained lower values. This demonstrates that leaf temperature is closely linked to transpiration efficiency and canopy density. (Zhang et al., 2024). Elevated leaf temperature in plants is generally associated with reduced photosynthetic capacity, while lower canopy temperature reflects more efficient water use (Sofi et al., 2019). Consistent with this, previous studies have shown that microbial fertilizers can enhance stomatal conductance and water use efficiency (Ozaktan et al., 2025). The negative correlations observed between thermal parameters and both SPAD and NDVI in our study are consistent with previous findings indicating that thermal imaging is a sensitive tool for early detection of plant stress (Souza et al., 2025). Overall, the results suggest that Fe application increased water retention within plant tissues but limited dry matter accumulation, a response aligned with studies reporting that Fe affects osmotic balance and chloroplast function (Roosta et al., 2018). In contrast, urea enhanced tissue water content and stimulated biomass development due to improved nitrogen availability and associated physiological activity (Abou El-Hassan et al., 2022). Thermal imaging results highlighted the role of fertilization strategies in regulating water use efficiency and stress tolerance, with urea and microbial fertilizers particularly enhancing physiological resilience.

4.3. Sensor based parameters and their potential for yield prediction

The study revealed that SPAD and NDVI values exhibited strong positive correlations with post-harvest biomass parameters (fresh and dry weight), confirming that sensor-based measurements are reliable indicators for yield prediction in cowpea. Similar findings in maize have reported that SPAD values correlate with grain yield at levels of 95–99%, demonstrating the high predictive capacity of chlorophyll indices, particularly during reproductive stages (Shivashankar et al.,

2025). Consistent with this, the relationships observed in our study align with previous reports indicating that NDVI is one of the key parameters reflecting biomass accumulation during the vegetative growth phase (Hou et al., 2025). Multivariate analysis further supported these associations, as SPAD and NDVI clustered with biomass-related traits along PC1, strengthening their explanatory power for yield performance. Comparable trends have been reported in wheat, where NDVI and INSEY indices contributed most strongly to yield prediction models across Zadoks stages, achieving R^2 values exceeding 0.80 when integrated with machine learning algorithms (Rufaioglu et al., 2025). Studies on micronutrient imbalances similarly support these observations; in particular, Fe and Zn deficiencies have been shown to markedly alter chlorophyll content, PSII photochemical efficiency, and biomass formation, thereby influencing optical sensor responses (Roosta et al., 2018). Additionally, enhanced Zn and Fe nutrition has been reported to improve water-use dynamics, osmotic balance, and photosynthetic performance under stress, which may modify thermal signatures and optical sensor behavior (Dehnavi and Sheshbahre, 2017). In our study, the negative correlations between thermal parameters and both SPAD and NDVI indicated that thermal sensors can serve as complementary tools for the early detection of stress conditions. This finding is consistent with studies demonstrating that thermal imaging provides early signals of water stress, while microbial fertilizers may enhance stomatal conductance and water-use efficiency (Souza et al., 2025). Taken together, the results suggest that optical sensor indicators such as SPAD and NDVI play a central role in biomass and yield prediction, whereas thermal parameters provide valuable complementary insights related to stress detection. This integrated approach holds strong potential for the development of machine learning- and remote sensing-based decision support systems for future cowpea yield prediction (Rufaioglu et al., 2025).

4.4. Contributions and limitations of study

This study is distinguished by several key contributions. The dominant effect of urea across all physiological and yield parameters, the moderate yet sustainable contributions of microbial fertilizers, the specific role of Fe in water relations, and the use of thermal data as a stress indicator together highlight the novelty of this work. The combined use of multivariate analytical tools such as radar diagrams, correlation matrices, and PCA provided an integrated rather than a one-dimensional perspective on fertilizer effects. In this respect, the study extended beyond conventional agronomic observations and contributed directly to digital agriculture applications. Nevertheless, some limitations should be acknowledged. First, the experiment was conducted under controlled greenhouse conditions, which may not fully capture the influence of field factors such as soil heterogeneity, climatic variability, and biotic stresses. Moreover, the study was limited to a single growing season, and inter-annual variability could not be assessed. Fertilizer doses and application methods were also restricted; therefore, future studies should evaluate a wider range of combinations and dosage levels. Despite these limitations, the findings are of practical and scientific relevance. Urea application emerged as the most effective strategy for optimizing biomass and yield, while microbial fertilizers presented a strong alternative from the perspective of environmental sustainability. The distinct role of Fe in water relations provides potential for future research under drought and salinity stress conditions. Furthermore, the study demonstrated that sensor-based monitoring tools (SPAD, NDVI, thermal imaging) can be employed for early yield prediction, thereby contributing to the development of machine learning-based decision support systems.

5. Conclusion

This study comprehensively evaluated the effects of different fertilizer applications (urea, Zn, Fe, and microbial fertilizers) on the physiological, morphological, and yield

parameters of cowpea (*Vigna unguiculata* L.) using modern sensor-based approaches (SPAD, NDVI, and thermal imaging). The findings revealed that urea application exerted a dominant effect across all growth parameters (SPAD, NDVI, plant height, fresh and dry biomass). Microbial fertilization provided moderate but sustainable contributions to photosynthetic capacity and biomass accumulation, whereas Zn showed limited effects. Fe application increased plant moisture content (MC) and H₂O/DM ratio, thereby enhancing water retention capacity, although it constrained dry matter accumulation. Thermal imaging results demonstrated that leaf temperatures were higher in the control group but remained lower under urea and microbial treatments, indicating the effectiveness of these fertilizers in reducing plant stress. Correlation and PCA analyses confirmed strong positive relationships between SPAD, NDVI, and post-harvest biomass, validating their potential as reliable indicators for early yield prediction. Radar diagrams and multivariate analyses further illustrated the comprehensive positive effects of urea and highlighted the notable contributions of microbial fertilizers in the context of sustainable agriculture. Overall, urea application can be considered the most effective strategy for enhancing biomass and yield in cowpea, while microbial fertilizers represent an environmentally sustainable alternative. Fe application plays a complementary role, particularly in water relations. The study underscores the value of sensor-based monitoring techniques (SPAD, NDVI, thermal imaging) as powerful tools for assessing fertilizer efficiency and yield prediction, providing a robust foundation for future integration into machine learning and digital agriculture applications.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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