



RESEARCH ARTICLE

Iron (Fe) Nutrient Dynamics in Oil Palm Leaves

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Abstract

Iron (Fe) management is crucial in cultivating oil palm, especially in sandy soils, due to its essential role in supporting photosynthesis and palm metabolism, directly influencing the quality and productivity of oil palms. This study aimed to explore the dynamics of Fe deficiency in oil palm leaves in Central Kalimantan, Indonesia. Using a Split Plot Design, the study compared plant conditions between the control (T0) and three levels of Fe deficiency: low (T1), moderate (T2), and severe (T3). Palm samples were selected using the purposive sampling method. Laboratory analysis of leaf samples indicated a significant decrease in Fe content in deficient palms, with levels of 41.49 µg/g in T1, 42.59 µg/g in T2, and 38.93 µg/g in T3, compared to the control group, which had 67.25 µg/g. The study also revealed that Fe deficiency affects the absorption of other macro and micronutrients. For instance, nitrogen levels increased under moderate Fe deficiency (2.57%), while potassium levels decreased (0.729%) at the same level. Despite the Fe deficiency, the plants adapted by maintaining other nutrient levels within a moderate range. Under severe Fe deficiency conditions, Cu levels reached their highest (5.868 µg/g), while Fe showed a significant decrease. This confirms that oil palm has complex nutrient adaptation and regulation mechanisms to maintain nutrient balance even under deficient conditions. These results emphasize the importance of Fe management in oil palm plantations, especially in sandy soils that are prone to nutrient deficiency.

Keywords

fe deficiency; oil palm; leaf nutrients; nutrient absorption; plant adaptation

Introduction

Oil palm (*Elaeis guineensis* Jacq.) plantations are crucial to Indonesia's economy, significantly contributing to its Gross Domestic Product (GDP). The sector has seen rapid growth, particularly in regions with sandy soil conditions, such as parts of Central Kalimantan. Sandy soils present significant challenges in nutrient management due to their low nutrient and water availability, which adversely affects the quality and productivity of oil palms (1,11). One of the frequent and impactful nutritional problems in these plantations is iron (Fe) deficiency.

Fe is an essential element for the growth and productivity of oil palms, playing a crucial role in photosynthesis, chlorophyll synthesis, and various metabolic processes (3). Fe can be sourced from soil, organic and inorganic fertilizers, and other Fe-rich soil amendments (4). In the soil, Fe is available in various forms, including Fe²⁺ (ferrous) and Fe³⁺ (ferric), and its solubility

and availability are influenced by soil pH and redox conditions (5). Oil palms primarily absorb Fe in the form of Fe^{2+} ions, which are more readily taken up by plant roots than Fe^{3+} (6). The Fe absorption mechanism in plants involves the reduction of Fe^{3+} to Fe^{2+} in the rhizosphere by root reductase enzymes, facilitating Fe movement through the root membrane and its transport throughout the plant to support biological processes (7,8).

Iron deficiency in oil palms can cause significant growth disturbances (9). Symptoms of Fe deficiency appear on the youngest fronds, which become flaccid and show uneven yellowing and white spots (10). In severe cases, new leaflets may develop necrotic tips, growth is stunted, and the meristem may eventually die (11). A critical level of 50 mg Fe/kg dry weight in the 17th frond has been identified as essential for oil palm growth (12). Fe deficiency is typically not caused solely by a lack of Fe in the soil but can also result from poor soil aeration, planting oil palms too deeply, or root damage due to root rot diseases (13,14,15). While high soil pH is not a common cause of Fe deficiency in oil palm, excessive absorption of other nutrient ions can lead to symptoms of Fe deficiency (11). Effective treatments for Fe deficiency include the application of iron sulfate or chelated compounds, such as FeDTPA, FeEDDHA, or FeHEEDTA, depending on soil conditions. Additionally, stem injections using FeSO_4 have been reported to be effective (16,17,18).

Given the importance of Fe in oil palm cultivation, this study aimed to explore the dynamics of Fe deficiency and its relationship with macro- and micronutrients in oil palm leaves. Using experimental and analytical approaches, this study seeks to provide new insights into the management of oil palm nutrition in sandy soils. Additionally, it aims to offer practical recommendations to address Fe deficiency and sustainably enhance oil palm production.

Materials and Methods

A. Site Location

The study was conducted in an oil palm plantation in Central Kalimantan Province, Indonesia. The plantation area covers 80,000 ha with flat to slightly undulating topography, and the elevation ranges between 5 and 32 m above sea level (Figure 1). This location was chosen due to its extensive sandy soil characteristics, making it ideal for researching the dynamics of Fe deficiency in oil palm cultivation.

B. Research Design

This study employed a Split Plot Design to assess 3 levels of Fe deficiency in oil palms: low (T1), moderate (T2), and severe (T3). A control (T0) was used to compare leaves experiencing Fe deficiency with those under normal conditions. Each treatment was repeated 10 times. Samples were selected through purposive sampling based on initial census results regarding Fe deficiency in oil palm plantations. The selection of locations and sample plants was intentionally focused on areas exhibiting various levels of Fe deficiency symptoms, from low to severe, to obtain a comprehensive understanding of the dynamics of Fe deficiency and its effects on oil palm.

C. Data Collection

Data were collected using two primary methods: visual observation and laboratory analysis. Visual observations were employed to identify symptoms of Fe deficiency in the oil palm leaves, such as interveinal chlorosis. Trees for leaf sample collection were selectively determined using purposive sampling. Leaf samples were collected from leaf number 17 for macronutrient content analysis, including Fe (via Atomic Absorption Spectrophotometry or AAS), N (Kjeldahl method), P (Spectro UV-Vis method), K (AAS), Mg (AAS), and Ca (AAS). Additionally, leaf number 3 was used for micronutrient analysis, including B (Spectro UV-Vis), Cu

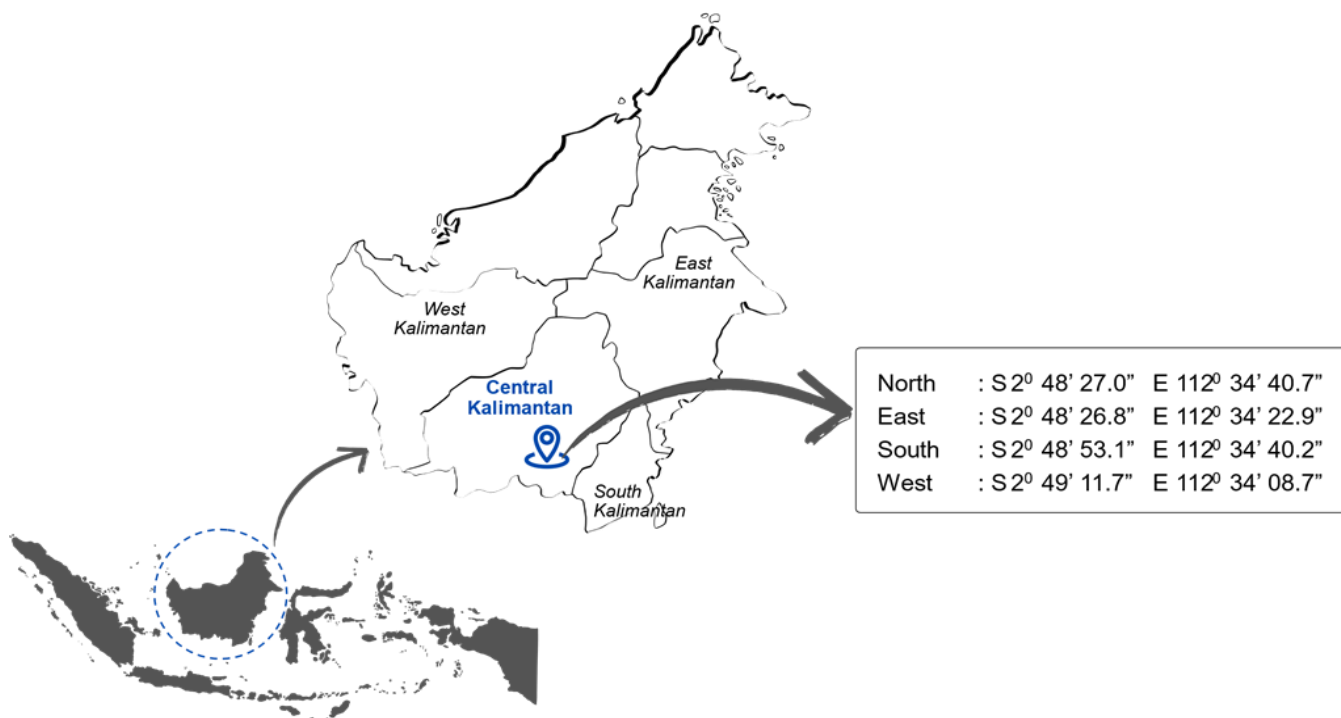


Figure 1. Site study

(AAS), and Zn (AAS) (19). This approach ensures accurate macro-and micronutrient analyses, providing a comprehensive overview of the plant's nutritional status.

D. Data Analysis

Data obtained from visual observations and laboratory analyses were analyzed using simple regression to evaluate the relationship between levels of Fe deficiency (independent variables) and leaf nutrient content (dependent variables). Additionally, Analysis of Variance (ANOVA) and Duncan's Multiple Range Test (DMRT) at a 5% significance level were conducted to strengthen the findings from the simple regression. ANOVA was employed to assess whether there were significant differences between groups based on Fe deficiency levels, testing the hypothesis that no difference exists between group means. If ANOVA results indicated significant differences, the DMRT was applied to determine which groups differed significantly. Statistical analysis was performed using SPSS Version 28 software and Python to determine the significance of the relationships between these variables (20).

The results of the leaf analysis were compared with the standard nutrient content for oil palms, as shown in Table 1. Nutrient content criteria were classified into low, moderate, and severe or high categories (21). The comparative test was crucial in supporting the discussion of this study. By comparing the results with established standards, the study provides detailed insights into the plant's nutritional status and helps formulate effective nutrient management strategies to enhance oil palm productivity.

Table 1. Standard Nutrient Levels in Oil Palm Leaves

Nutrient	Deficiency	Optimum	High
N (%)	< 2.30	2.4 – 2.8	> 3.0
P (%)	< 0.14	0.15 – 0.18	> 0.25
K (%)	< 0.75	0.9 – 1.2	> 1.6
Mg (%)	< 0.20	0.25 – 0.40	> 0,7
Ca	< 0.25	0.5 – 0.75	> 1.0
B (µg/g)	< 8	15 - 25	> 40
Cu (µg/g)	< 3	5 - 8	> 15
Zn (µg/g)	< 10	12 - 18	> 80
Fe (µg/g)	< 50	50 - 250	> 250

Sumber: Fairhurst dan Mutert (1999) (7)

Table 2. Duncan test results of oil palm leaf nutrient content based on Fe deficiency levels

Treatment	Leaf Analysis Results								
	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	B (µg/g)	Cu (µg/g)	Zn (µg/g)	Fe (µg/g)
T0	2.38 ^b	0.160 ^a	0.910 ^b	0.382 ^b	0.722 ^a	15.15 ^{ns}	5.344 ^b	15.17 ^{ns}	67.25 ^c
T1	2.29 ^{ab}	0.164 ^b	0.872 ^b	0.362 ^b	0.742 ^a	16.86 ^{ns}	3.194 ^a	16.21 ^{ns}	41.49 ^{ab}
T2	2.57 ^c	0.175 ^c	0.729 ^a	0.359 ^b	0.869 ^b	14.74 ^{ns}	4.641 ^{bc}	16.10 ^{ns}	42.59 ^b
T3	2.20 ^a	0.160 ^{ab}	0.852 ^b	0.302 ^a	0.747 ^a	14.83 ^{ns}	5.868 ^c	16.55 ^{ns}	38.93 ^a

Note: Numbers followed by the same letter within a column indicate no significant difference based on Duncan's test α 5%

Results

The analysis of nutrient content in oil palm leaves based on Fe deficiency levels revealed notable patterns in nutrient absorption. As shown in Table 2, there were significant differences in Fe content between the control and the various levels of Fe deficiency. The control group exhibited the highest Fe content, followed by mild (T1), moderate (T2), and severe (T3) deficiencies. Even at low Fe deficiency (T1), the Fe levels were higher than those observed in severe Fe deficiency. Interestingly, the highest nitrogen (N) level was recorded in the moderate Fe deficiency treatment (T2, at 2.57%). This was significantly higher than the nitrogen level in the severe Fe deficiency treatment (T3), which was 2.20%. This suggests that moderate Fe deficiency may enhance nitrogen absorption or metabolism. The control group (T0) and the low Fe deficiency group (T1) showed nitrogen levels that were not significantly different from each other, and both fell within a similar range.

The analysis revealed significant differences in phosphorus (P) levels across treatments. The highest P level was observed in the moderate Fe deficiency treatment (T2) at 0.175%, which differed significantly from both the severe Fe deficiency treatment (T3) and the control (T0). However, the low Fe deficiency treatment (T1) and the severe Fe deficiency treatment (T3) did not show significant differences, indicating a similar effect of Fe deficiency on phosphorus availability at these levels. Potassium (K) levels exhibited a different pattern. The lowest K level was found in the moderate Fe deficiency treatment (T2) at 0.729%, which differed significantly from both the control (T0) and the severe Fe deficiency treatment (T3). This suggests that moderate Fe deficiency reduces K absorption. There were no significant differences in K levels between the low Fe deficiency treatment (T1) and the control (T0) or the severe Fe deficiency treatment (T3), indicating that the effects of low Fe deficiency on K absorption are similar to those observed under control and severe Fe deficiency conditions.

Magnesium (Mg) levels were found to be the lowest in the severe Fe deficiency treatment (T3, 0.302%). No significant differences were observed between the control (T0), low Fe deficiency (T1), and moderate Fe deficiency (T2), indicating that Fe deficiency had minimal impact on Mg levels from the control to moderate deficiency conditions. Calcium (Ca) levels were significantly affected by moderate Fe deficiency differing markedly from the control (T0), low Fe deficiency (T1), and severe Fe

deficiency (T3). However, levels of boron (B) and zinc (Zn) showed no significant differences between treatments, indicating that Fe deficiency did not significantly affect the content of these nutrients in the leaves. A related pattern was observed between copper (Cu) and iron (Fe), with the highest Cu level and the lowest Fe level recorded under severe Fe deficiency (T3, Cu: 5.868%, Fe: 38.93 µg/g). This indicates a negative effect of severe Fe deficiency on Fe content in the leaves while concurrently increasing Cu levels.

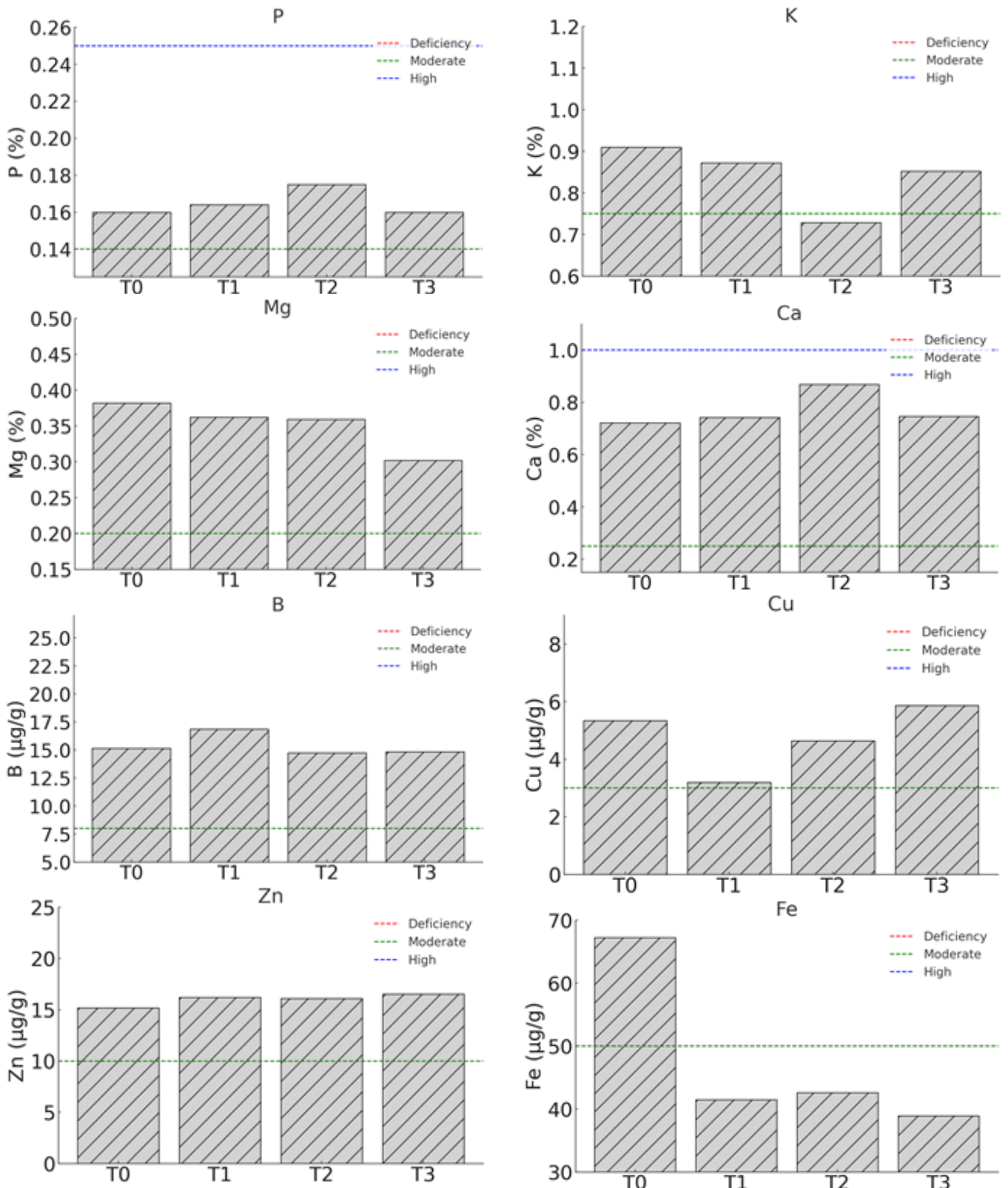


Fig. 2 Comparison of Nutrient Levels in Oil Palm Leaves for each treatment

Analysis of nutrient content in oil palm leaves about Fe deficiency levels (T0, T1, T2, and T3) compared to standard nutrient levels for oil palm leaves revealed diverse and informative patterns of nutrient absorption (Figure 2). The N level in T2 (2.569%, Moderate) was similar to that in T0 (2.378%, moderate), while T1 (2.291%) and T3 (2.200%) fell within the deficiency range, indicating the impact of Fe deficiency on N absorption. P levels in all treatments were moderate, ranging from 0.160% to 0.175%, suggesting that Fe deficiency did not significantly affect P absorption. K levels in T2 (0.729%, deficiency) showed a significant decrease compared to T0, T1, and T3, all of which were moderate, indicating that moderate Fe deficiency adversely affected K absorption.

The Mg levels in all treatment groups remained within the moderate range, although T3 (0.302%) was at the

lower end, indicating a potential impact of severe Fe deficiency on Mg absorption. Ca levels were moderate across all treatments, with T2 (0.869%) showing the highest level, suggesting that Fe deficiency did not significantly affect Ca absorption. B, Cu, and Zn levels were also within the moderate range across all treatments, indicating that Fe deficiency did not significantly impact the absorption of these micronutrients.

However, Fe exhibited different conditions, with T1 (41.491 $\mu\text{g/g}$), T2 (42.589 $\mu\text{g/g}$), and T3 (38.929 $\mu\text{g/g}$) all indicating deficiency, contrasting with T0 (67.250 $\mu\text{g/g}$, moderate), thereby confirming the impact of Fe deficiency on iron absorption in oil palm leaves. This analysis of leaf nutrient content elucidates that Fe deficiency has a varied impact on the absorption of various nutrients in oil palm leaves, particularly affecting N, K, and Zn, indicating deficiencies in these elements.

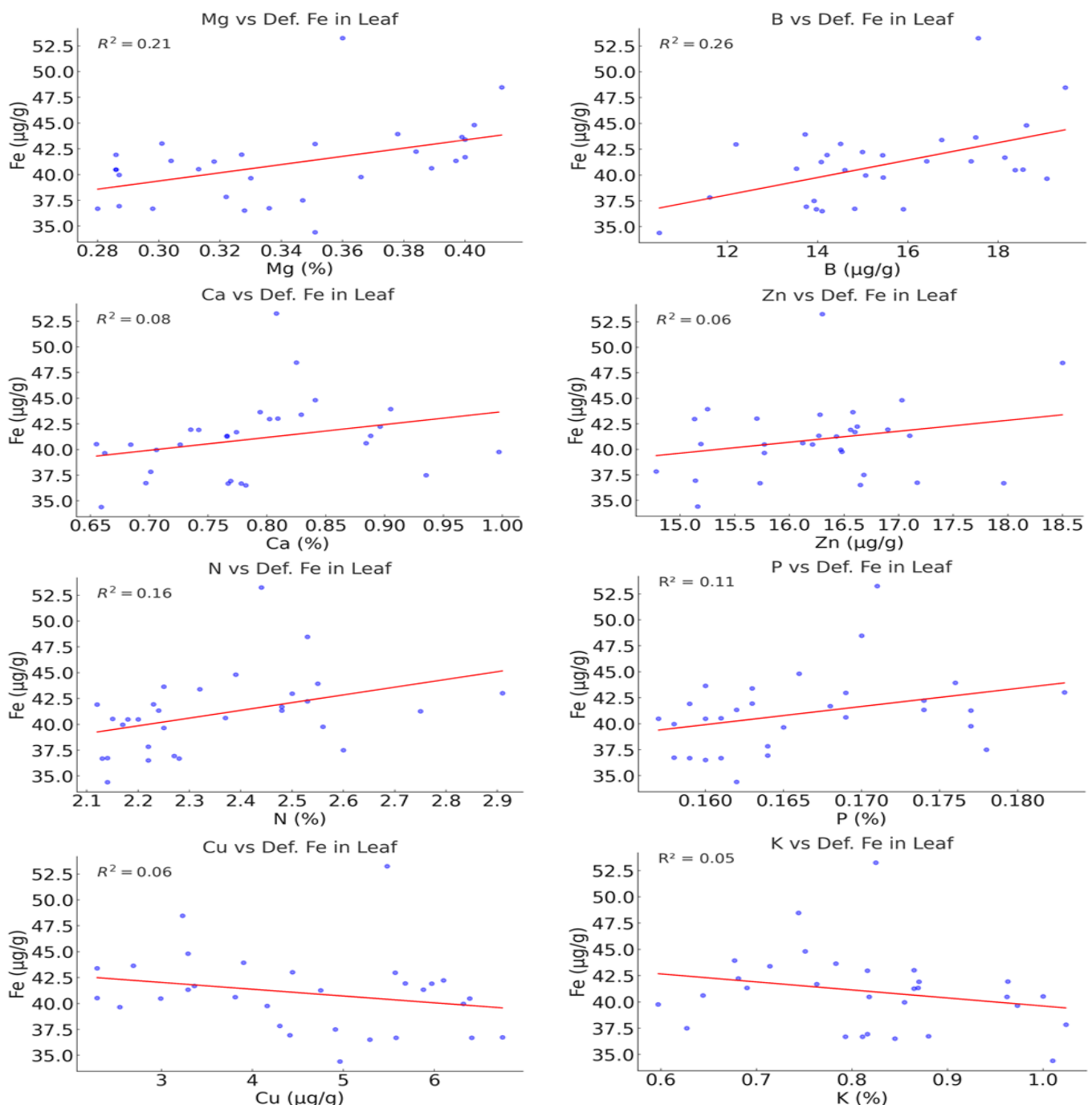


Fig. 3 Relationship between Nutrient Concentrations and Fe in Oil Palm leaves experiencing Fe deficiency (T1, T2, and T3)

The scatterplot depicted in Figure 3 illustrates the relationship between nutrient concentrations (N, P, K, Mg, Ca, B, Cu, and Zn) on the x-axis and Fe concentrations in oil palm leaves on the y-axis. The analysis revealed positive correlations among N, P, Mg, Ca, B, and Zn with Fe levels, as evidenced by the red regression line indicating higher Fe concentrations with increased nutrient levels. Conversely, the regression lines for Cu and K showed a very slight negative slope, suggesting a weak and unclear negative relationship between Cu and K concentrations and Fe, although this trend was nearly flat.

The coefficient of determination (R^2) was notably low for some nutrients (Mg 21%, B 26%) and mostly very low for others (N 16%, P 11%, Ca 8%, Zn 6%, Cu 6%, K 5%), indicating that the variability in Fe concentrations in oil palm leaves could only be partly explained by variations in nutrient concentrations. While there are positive relationships observed with nutrients like N, P, Mg, Ca, B, and Zn, and negative relationships with Cu and K, the nutrient levels measured in the leaves provide limited predictive value for Fe concentrations. This suggests that factors beyond nutrient levels alone influence Fe availability in oil palm leaves under deficiency conditions, emphasizing the importance of considering additional variables to fully comprehend Fe dynamics in these plants.

Discussion

The analysis of the interaction between Fe deficiency and nutrient absorption in oil palm leaves revealed complex and varied dynamics. Despite a significant decrease in Fe levels across all deficiency levels (T1, T2, and T3) compared to the control (T0), most other nutrients remained within moderate ranges. The highest N level observed under moderate Fe deficiency (T2) suggested potential increased N metabolism or absorption despite the deficiency. In contrast, N levels in low and severe deficiency, as well as the control, did not exhibit significant differences, indicating some levels of resilience or adaptation to fluctuations in Fe levels.

Although Fe deficiency did not significantly affect P absorption in oil palm leaves, there was a notable decrease in K absorption, indicating its sensitivity to varying levels of Fe deficiency. Across all treatments, including the control, most nutrients remained within moderate ranges, with Mg and Ca levels also maintaining moderation, despite a slight decrease in Mg observed in T3. This suggests that the plant can maintain adequate Mg and Ca nutrient levels, possibly due to specific ion interactions and the roles these nutrients play in stress tolerance.

Specific ion interactions between Ca and Mg, which do not directly compete with Fe for binding sites or transport pathways in plants, facilitate even in the presence of Fe deficiency (22). Studies have demonstrated that Mg²⁺ binding to CBD2 stabilizes it and alters its affinity for Ca²⁺ (23). CBD2 effectively binds two Ca²⁺ ions at specific Ca²⁺-binding sites I and II. Moreover, Ca and Mg ions compete for binding sites in proteins like β -lactalbumin and

lysozyme, but this competition does not occur directly with Fe in plants (24). The impact of Ca and Mg concentrations in water on iron absorption by *Microcystis* varies depending on the type of ligand involved (25). Maintaining a homeostatic balance between Ca²⁺ and Mg²⁺ within plant cells is critical for optimal growth and development, underscoring the significant antagonistic interactions between these ions (26).

Magnesium (Mg) and calcium (Ca) are crucial components that assist plants in coping with other nutrient deficiencies. During stressful conditions, Mg and Ca levels increase, enabling the plant to conserve energy and activate calcium-dependent signaling pathways (27). Plants require a balanced homeostasis between Ca²⁺ and Mg²⁺ for optimal growth and development, making the maintenance of this equilibrium a critical response to changes in their nutritional status (26). Chromium (Cr) stress affects Ca and Mg concentrations in rice plants, leading to reduced biomass (28). Ca²⁺ signals play a role in responding to stress by increasing intracellular Ca concentrations, thereby serving as a stress-induced signal transduction pathway (29). Additionally, Ca²⁺ is essential for activating plant tolerance mechanisms to stresses such as cold, drought, and high salinity (30). Iron (Fe) plays a vital role in alleviating stress caused by salinity, drought, and heavy metals by activating plant antioxidant enzymes such as catalase, peroxidase, and superoxide dismutase (31).

The interaction between Fe deficiency and the absorption of micronutrients such as B, Cu, and Zn generally showed no significant differences, indicating that the plant's Fe status did not significantly affect the absorption of these micronutrients. However, the increase in Cu levels under severe Fe deficiency (T3) conditions, coupled with a drastic drop in Fe levels, suggested a compensatory or antagonistic mechanism for maintaining nutritional balance during deficiency. While Fe deficiency does affect the levels of some nutrients in oil palm leaves, most nutrients remain within moderate ranges, highlighting the plant's ability to adapt to nutritional stress. The significant decrease in N and K absorption at certain deficiency levels underscores the sensitivity of these specific nutrients to Fe deficiency. Overall, the plant demonstrates resilience in maintaining essential physiological functions even under suboptimal conditions. Micronutrients are transported through different mechanisms in plants; Fe, for instance, is generally transported via a specific protein system distinct from those for B, Cu, and Zn. The finely tuned Fe homeostasis mechanism in *Arabidopsis halleri* maintains optimal Fe levels and prevents excessive Zn absorption, contributing to its zinc tolerance compared to *Arabidopsis thaliana* (32). Micronutrients play diverse and essential roles in plant growth, exemplified by their involvement in various biological processes such as those governed by Zn, B, and Fe (33).

Overall, the findings of this study indicate that despite reduced Fe levels across all deficiency levels studied, oil palm plants were capable of maintaining other nutrient

levels—such as N, P, K, Mg, Ca, B, Cu, and Zn—within moderate ranges. This suggests the presence of adaptive mechanisms enabling plants to cope with nutritional stress. The notable decrease in N levels under moderate Fe deficiency may reflect the plant's response to enhance N absorption and metabolism in the face of Fe stress. In contrast, stable P levels suggest that phosphorus absorption is less affected by Fe deficiency. Although there are weak positive and negative relationships between nutrient concentrations and Fe levels in oil palm leaves experiencing Fe deficiency, these nutrient concentrations alone do not sufficiently explain the variability in Fe concentrations. This underscores the necessity of considering additional factors to comprehensively understand the dynamics of Fe availability in Fe-deficient oil palms.

In the context of Fe deficiency in oil palms, various factors interact to affect nutrient absorption and utilization by plants. Plant adaptation mechanisms are crucial, allowing plants to adjust genetic expression and enzymatic activity to enhance the absorption and use of available nutrients under Fe-deficient conditions. For example, the increased expression of the nicotianamine synthase gene improves nutrient quality and tolerance to Fe deficiency in plants such as rice, soybean, and sweet potato (34). Additionally, plants adjust their internal metabolic processes through the secretion of chelators and reductive and proton-proton processes (35). Nutrient interactions also play a significant role. Fe deficiency can alter the absorption and metabolism of N and K, which can interact antagonistically or synergistically, resulting in complex nutrient absorption dynamics (36). Furthermore, the absorption of micronutrients like copper (Cu) may increase as a physiological response to Fe deficiency, which is crucial for maintaining plant physiological functions (37).

Soil conditions, such as interactions between Fe and soil components, can inhibit or facilitate the absorption of other nutrients by plant roots, significantly impacting nutrient availability (38). Environmental variables, such as soil pH and moisture, influence the solubility and mobility of Fe and other nutrients, thereby affecting their absorption by plants (39). Additionally, the status of other nutrients in the soil, including their availability and balance, plays a crucial role in Fe absorption and plant responses to Fe deficiency (40). Overall, factors such as plant adaptation mechanisms, nutrient interactions, soil conditions, and environmental variables collectively and often complexly affect how oil palm plants manage nutrients under Fe-deficient conditions. This highlights the importance of a holistic approach to plant nutrient management (41).

Conclusion

Fe deficiency significantly decreases Fe levels in oil palm leaves, with measurements dropping from 67.25 $\mu\text{g/g}$ under control conditions to 41.49 $\mu\text{g/g}$ under low deficiency, 42.59 $\mu\text{g/g}$ under moderate deficiency, and

38.93 $\mu\text{g/g}$ under severe deficiency. Despite this reduction, the plants displayed remarkable adaptation by maintaining other nutrient levels within moderate ranges. The increased N level under moderate Fe deficiency conditions (2.57%) compared to severe deficiency (2.20%) indicates the plant's adaptability to nutritional stress. The highest P level (0.175%) and lowest K level (0.729%) were found under moderate Fe deficiency, highlighting the impact of Fe deficiency on the absorption and metabolism of other nutrients. Under severe Fe deficiency, Cu reached its highest level (5.868 $\mu\text{g/g}$) while Fe showed a significant decrease, confirming that oil palm plants possess complex nutrient adaptation and regulation mechanisms to maintain nutrient balance even in deficient conditions. This analysis demonstrates that oil palm plants can sustain essential physiological functions despite Fe deficiency, indicating effective resilience and adaptation to nutritional disturbances.

Future Aspects: To further enhance the resilience of oil palm plants, future research should focus on developing advanced fertilization strategies and biotechnological interventions to mitigate the effects of Fe deficiency more effectively. Additionally, exploring the genetic basis of nutrient adaptation in oil palms could lead to the development of more robust varieties capable of thriving in nutrient-poor soils. Implementing precision agriculture techniques and improving soil management practices will also be crucial for sustaining oil palm productivity in the face of nutritional challenges. By addressing these future directions, the oil palm industry can ensure sustainable cultivation practices that enhance plant health and yield, ultimately contributing to the overall stability and profitability of oil palm plantations.

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Authors' contributions

Each author in this paper contributes their own in writing: RAS as the main researcher, providing proposals and conducting research, writing research results and discussions, participating in aligning the sequence, and compiling manuscripts. The BJP participated in the design of the study. GII participates in sequence alignment. The JP participated in its design and coordination. S contributed to the design of the study, interpretation of data, and drafting of the manuscript. SP provided critical feedback and helped shape the research, analysis, and manuscript. FTS assisted with data collection and analysis. All authors have read and approved the final manuscript.

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Compliance with ethical standards

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