

RESEARCH ARTICLE



Soil nutrient availability and nutrient uptake by cocoa plants based on leaf nutrient content under various fertilizer application methods

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**Abstract**

This study evaluated the effects of fertilizer placement methods on soil nutrient availability and cocoa leaf nutrient status. The experiment was conducted from 2 February to 2 April 2024 in Lawe Sagu Hulu Village, Southeast Aceh Regency, Indonesia, using a non-factorial randomized complete block design with three treatments stake, bracket, and disc each replicated six times. Soil total nitrogen (N), available phosphorus (P), exchangeable potassium (K), and leaf N, P, and K concentrations were measured before and after fertilization. Fertilizer placement did not significantly affect soil N or leaf N and P concentrations. The disc method produced the highest soil available P value (2.95), which was 31.1% and 32.3% higher than the stake and bracket methods, respectively. Soil exchangeable K was higher under the stake and bracket methods than under the disc method. The stake method produced the highest leaf K concentration (2.14%), exceeding the bracket and disc methods by 13.8% and 15.1%, respectively. These findings show that fertilizer placement affects soil nutrient retention and cocoa leaf nutrient status differently. The disc method may be considered when increasing soil P availability is the main objective, whereas the stake method may be more suitable for improving leaf K status. Site-specific recommendations should be supported by periodic soil and leaf analyses.

KEYWORDS

cocoa, fertilizer application methods, soil nutrients, leaf nutrient content

1. INTRODUCTION

The cocoa plant (*Theobroma cacao* L.) is one of the strategic plantation commodities that plays a vital role in the regional and national economies. Cocoa productivity is highly influenced by the availability of adequate nutrients in the soil, making nutrient management a crucial aspect of its cultivation system (Espinoza Herrera et al., 2022; Weinstein et al., 2025). In many smallholder

plantation areas, low fertilizer efficiency remains a major constraint that directly impacts vegetative growth, fruit set, and cocoa yield quality (Puspita et al., 2024; Santosa, 2024).

Fertilizer efficiency is determined not only by the type and dose of fertilizer applied but also by the application method used in the field. Fertilizer application methods influence fertilizer distribution, nutrient loss rates, and nutrient availability in the active root zone (Weinstein et al., 2025).

Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) play a crucial role in plant physiological processes, ranging from vegetative tissue formation, photosynthetic activity, to seed filling (Puentes-Páramo et al., 2014). Therefore, the availability of these nutrients in the soil will significantly determine the rate of uptake by cocoa plants.

Fertilizer efficiency is determined not only by the type and dose of fertilizer applied but also by the application method used in the field. Fertilizer application methods influence fertilizer distribution, nutrient loss rates, and nutrient availability in the active root zone.

Plant nutrient status is commonly evaluated through leaf analysis because leaf nutrient concentrations integrate the effects of nutrient availability in the soil, root acquisition, internal nutrient transport, and plant physiological demand. Consequently, leaf analysis can provide a more direct indication of the nutritional condition experienced by the plant than soil analysis alone (Murillo et al., 2013; Prado & Rozane, 2020). Nevertheless, soil nutrient availability and leaf nutrient concentrations represent related but distinct components of the soil–plant nutrient system. A high concentration of a nutrient in the soil does not necessarily result in a corresponding increase in leaf concentration because nutrient acquisition is also influenced by nutrient mobility, root distribution, soil moisture, root–fertilizer contact, and interactions among nutrients. Therefore, the simultaneous assessment of soil N, P, and K availability and leaf N, P, and K concentrations provides a more comprehensive basis for evaluating how fertilizer placement affects cocoa plant nutrient status.

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Previous studies have improved the understanding of nutrient management in cocoa, but their experimental emphasis has differed from that of the present study. Espinoza Herrera et al. (2022), for example, evaluated interactions among N, P, and K fertilization in relation to soil characteristics, vegetative growth, and fruit quality, whereas Weinstein et al. (2025) examined cacao growth, macronutrient demand, and water use under different N fertigation levels in controlled conditions. Meyer zu Drewer et al. (2022) demonstrated that fertilizer placement within the root zone could influence foliar P concentration and the growth of young cocoa plants; however, that investigation used biochar-based fertilizers in a pot experiment with cocoa seedlings. These studies provide important evidence regarding fertilizer rates, nutrient interactions, and localized root-zone application, but they do not directly explain how conventional mineral fertilizer placement patterns affect both soil nutrient availability and leaf nutrient status in productive cocoa trees under field conditions.

Accordingly, a specific knowledge gap remains regarding the comparative effects of stake, bracket, and disc fertilizer placement methods on the distribution of soil nutrients and their corresponding concentrations in cocoa leaves. Evidence is particularly limited for studies that evaluate soil and leaf N, P, and K simultaneously before and after fertilizer application under smallholder plantation conditions. The present study addresses this gap by comparing three fertilizer placement methods in a productive cocoa plantation in Southeast Aceh and by jointly evaluating changes in soil total N, available P, and exchangeable K, together with leaf N, P, and K concentrations. This paired soil–leaf assessment provides field-based information on whether fertilizer placement methods that increase nutrient availability in the soil also correspond to

improved plant nutrient status. Therefore, this study aimed to determine the effects of stake, bracket, and disc fertilizer placement methods on soil nutrient availability and cocoa plant nutrient status, as indicated by leaf N, P, and K concentrations.

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2. METHODS

2.1 Study site and initial soil characteristics

The study was conducted from 2 February to 2 April 2024 in a productive cocoa plantation located

in Lawe Sagu Hulu Village, Lawe Bulan Subdistrict, Southeast Aceh Regency, Aceh Province, Indonesia. The experimental site was located at 4°10'40.4" N and 97°12'43.4" E, corresponding to 4.177889° N and 97.212056° E. The location of the field study site in Lawe Sagu Hulu Village, Lawe Bulan Subdistrict, Southeast Aceh Regency, Aceh Province, Indonesia, is presented in [Figure 1](#). The selected plantation represented the prevailing cocoa-production conditions in the study area. Productive cocoa trees with relatively uniform age, canopy development, and general growth condition were selected to minimize initial variation among experimental units. Soil and leaf nutrient analyses were conducted at the Soil and Plant Laboratory following standard analytical procedures.

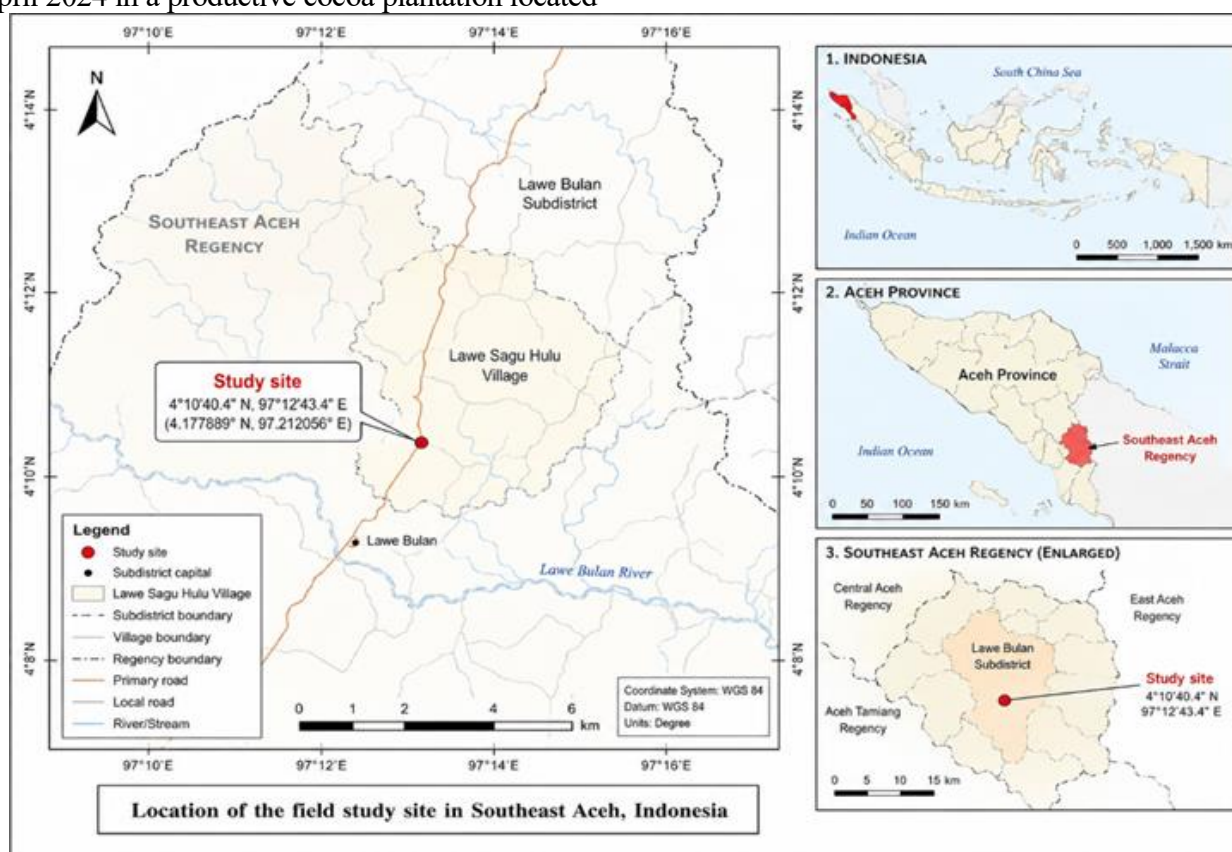


Figure 1. Location of the field study site in Lawe Sagu Hulu Village, Lawe Bulan Subdistrict, Southeast Aceh Regency, Aceh Province, Indonesia.

Before fertilizer application, initial soil characterization was conducted using 18 independent composite soil samples, corresponding to the 18 experimental units. Each composite sample consisted of four soil subsamples collected from different points around the active root zone of each experimental tree at a depth of 0–20 cm. The subsamples were thoroughly mixed and homogenized to produce one representative composite sample for each experimental unit. Soil samples were air-dried, gently crushed, and passed through a 2-mm sieve before laboratory analysis.

Each composite sample consisted of four soil subsamples collected from different points around the active root zone of each experimental tree at a depth of 0–20 cm.

Soil pH was measured potentiometrically in a 1:2.5 soil-to-water suspension. Soil organic carbon was determined using the Walkley–Black method, while soil organic matter was calculated by multiplying the organic carbon concentration by 1.724. Soil particle-size distribution was determined using the hydrometer method, and the textural class

was identified using the USDA textural triangle. Total nitrogen was determined using the Kjeldahl method, available phosphorus using the Bray I extraction method, and exchangeable potassium and cation exchange capacity using 1 M ammonium acetate extraction at pH 7. The initial physicochemical characteristics of the experimental soil are presented in [Table 1](#). Soil pH, organic carbon, organic matter, total nitrogen, available phosphorus, and exchangeable potassium were determined to characterize the initial fertility status of the experimental soil. These soil properties provide complementary information on the physical and chemical conditions affecting nutrient availability in cocoa-growing soils (Arthur et al., 2022).

Total nitrogen was determined using the Kjeldahl method, available phosphorus using the Bray I extraction method, and exchangeable potassium and cation exchange capacity using 1 M ammonium acetate extraction at pH 7.

Table 1. Initial physicochemical characteristics of the experimental soil before fertilizer application

Soil property	Comparison value	Unit	Analytical method
Soil pH (H ₂ O, 1:2.5)	5.42	–	Potentiometric method
Soil organic carbon	1.36	%	Walkley–Black method
Soil organic matter	2.34	%	Organic C × 1.724
Total nitrogen	0.20	%	Kjeldahl method
Available phosphorus	18.0	%	Bray I method
Exchangeable potassium	0.39	cmol(+) kg ⁻¹	1 M NH₄OAc extraction

2.2 Experimental materials and design

Productive cocoa trees (*Theobroma cacao* L.) approximately 8–10 years old were used as the experimental plants. The selected trees had relatively uniform canopy size, stem condition, and general growth performance. Trees showing severe pest or disease symptoms, substantial physical damage, or abnormal growth were excluded to minimize initial variability among experimental units. The trees were planted at a spacing of 3×3 m under the existing plantation-management system. NPK Phonska compound fertilizer containing 15% N, 15% P_2O_5 , and 15% K_2O was used as the fertilizer source.

The experiment was arranged in a non-factorial randomized complete block design with fertilizer placement method as the single treatment factor. Three fertilizer placement methods were evaluated: stake (S1), bracket (S2), and disc (S3). Each treatment was replicated six times, resulting in 18 experimental units. Six blocks were established based on the spatial position of the trees within the plantation and the similarity of their initial growth conditions to reduce the influence of small-scale field heterogeneity. Each block contained three experimental trees, and the three fertilizer placement treatments were randomly assigned to the trees within each block. Each experimental unit consisted of one cocoa tree, resulting in a total of 18 experimental trees. Based on the planting distance of 3×3 m, each tree represented an effective experimental area of approximately 9 m^2 . The same experimental trees were used for soil and leaf sampling before and after fertilizer application.

2.3 Fertilizer placement treatments and crop management

NPK Phonska compound fertilizer containing 15% N, 15% P_2O_5 , and 15% K_2O was applied once at the beginning of the experimental period at a rate of 500 g tree^{-1} . This rate supplied approximately 75 g N, 75 g P_2O_5 , and 75 g $K_2O \text{ tree}^{-1}$. All

experimental trees received the same fertilizer rate; therefore, the treatments differed only in the fertilizer placement method.

Under the stake method (S1), the fertilizer was divided equally among four vertical holes positioned at approximately equal distances around the canopy projection. Each hole received approximately 125 g of fertilizer and was prepared to a depth of 40–50 cm. The holes were arranged around the active root zone to distribute the fertilizer on four sides of the tree. Under the bracket method (S2), the fertilizer was divided equally between two semicircular trenches positioned on opposite sides of the tree along the canopy projection. Each trench received approximately 250 g of fertilizer and was prepared to a depth of 20–30 cm. The semicircular arrangement was intended to increase fertilizer contact with a broader section of the active root zone while avoiding direct fertilizer placement near the tree trunk. Under the disc method (S3), the fertilizer was distributed uniformly in one continuous circular trench constructed along the canopy projection. The trench was prepared to a depth of 20–30 cm, and the entire fertilizer dose was spread evenly around the tree to promote uniform nutrient distribution within the root zone. Following application, the fertilizer was covered with the excavated soil in accordance with the general principle of subsurface root-zone placement, which positions applied nutrients closer to the rooting zone while limiting direct exposure at the soil surface (Rychel et al., 2023). Schematic representation is presented in [Figure 2](#).

Immediately after fertilizer application, all holes and trenches were covered with the excavated soil to reduce fertilizer exposure, surface runoff, and nutrient loss. Weed control, pruning, pest and disease management, and other plantation-maintenance practices were applied uniformly to all experimental trees throughout the study. No additional fertilizer was applied during the experimental period.

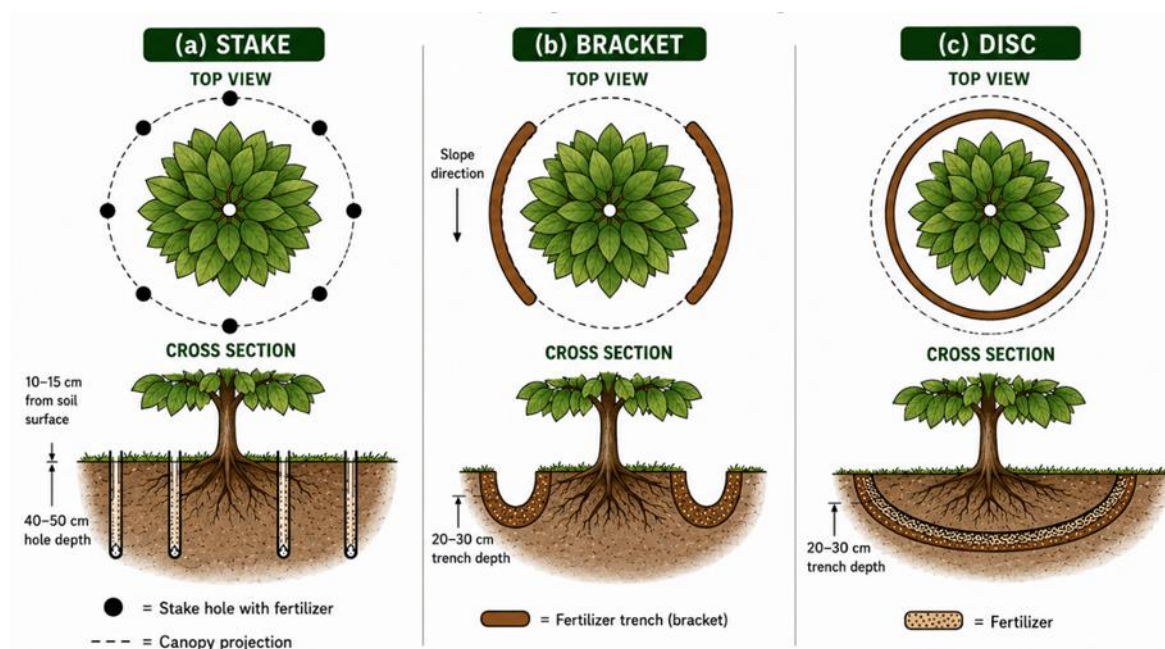


Figure 2. Schematic representation of the fertilizer placement treatments applied to cocoa trees: (a) stake method using four vertical holes, (b) bracket method using two semicircular trenches, and (c) disc method using one continuous circular trench along the canopy projection

2.4 Soil and leaf sampling and sample preparation

Soil and leaf samples were collected twice, immediately before fertilizer application and 60 days after treatment application. The same 18 experimental cocoa trees were sampled at both sampling times to ensure that changes in soil and leaf nutrient status were evaluated from the same experimental units.

Soil samples were collected from the active root zone of each experimental tree at a depth of 0–20 cm. Four soil subsamples were taken from four approximately equidistant points around the canopy projection, representing the main fertilizer-placement and root-activity zones. The four subsamples from each tree were thoroughly mixed to form one composite soil sample per experimental unit at each sampling time. Accordingly, 18 independent composite soil samples were obtained before treatment and another 18 composite samples after treatment, resulting in a total of 36 soil samples. Sampling tools were cleaned between experimental units to minimize cross-contamination. The

composite soil samples were placed in labeled polyethylene bags and transported to the laboratory. Samples were air-dried at room temperature, gently crushed, homogenized, and passed through a 2-mm sieve before chemical analysis. Visible plant residues, stones, and other foreign materials were removed during sample preparation.

Leaf samples were collected from mature, fully expanded leaves located in the middle canopy of each experimental tree. The selection of mature, fully expanded leaves and the distribution of sampling positions around the canopy followed the general approach used in recent nutrient-assessment studies on cocoa (Schmidt, Hasan, Ward, Firl, & Khalsa, 2025). Eight leaves were collected per tree, consisting of two leaves from each of the four cardinal directions—north, east, south, and west—to reduce variation associated with canopy position and sunlight exposure. Leaves showing symptoms of pest attack, disease, physical damage, senescence, or abnormal development were excluded. The same sampling criteria were applied before and after fertilizer treatment. Leaf samples

were placed in individually labeled paper bags and transported to the laboratory. The leaves were initially washed with clean water followed by distilled water to remove dust and surface contaminants. The samples were oven-dried at 65°C until a constant weight was reached, ground to a fine powder, passed through a 0.5-mm sieve, and stored in sealed labeled containers before nitrogen, phosphorus, and potassium analysis.

2.5 Laboratory analysis of soil and leaf nutrients

Soil and leaf nutrient analyses were conducted at the Soil and Plant Laboratory using standard analytical procedures. Soil samples were analyzed for total nitrogen, available phosphorus, and exchangeable potassium. Soil total nitrogen was determined using the Kjeldahl method, which involved acid digestion, distillation, and titration. Available phosphorus was extracted using the Bray I solution and quantified using the molybdenum-blue method with a UV–visible spectrophotometer at a wavelength of 882 nm. Exchangeable potassium was extracted using 1 M ammonium acetate at pH 7.0 and measured using a flame photometer. Soil total nitrogen, available phosphorus, and exchangeable potassium were expressed as percentage, mg kg^{-1} , and $\text{cmol}(+) \text{kg}^{-1}$, respectively. For leaf nutrient analysis, approximately 0.50 g of oven-dried and finely ground leaf material was used for each analytical sample. Leaf nitrogen concentration was determined using the Kjeldahl method. Leaf phosphorus and potassium were determined following wet digestion using a nitric acid–perchloric acid mixture. Phosphorus concentration in the resulting digest was quantified using the molybdenum-blue spectrophotometric method at 882 nm, whereas potassium concentration was determined using a flame photometer. Leaf nitrogen, phosphorus, and potassium concentrations were expressed as percentages of leaf dry matter.

All soil and leaf samples were analyzed according to the same analytical procedures to ensure comparability between the initial and post-

treatment measurements. Soil nutrient measurements were used to represent nutrient availability in the root zone, whereas leaf N, P, and K concentrations were used as indicators of cocoa plant nutrient status. The analytical framework was consistent with procedures used in cacao nutritional studies, in which nitrogen and mineral-element concentrations are determined from dried and ground plant tissues following digestion and instrumental analysis (Arévalo-Hernández et al., 2022). Leaf nutrient concentrations were not interpreted as total nutrient uptake or nutrient-use efficiency because plant biomass and whole-plant nutrient accumulation were not measured.

2.5 laboratory analysis of soil and leaf nutrients

Soil total nitrogen, available phosphorus, exchangeable potassium, and leaf nitrogen, phosphorus, and potassium concentrations were analyzed separately. Because soil and leaf samples were collected from the same experimental trees before and 60 days after fertilizer application, the data were analyzed using a repeated-measures linear mixed-effects model. Fertilizer placement method (stake, bracket, and disc), sampling time (before and after fertilizer application), and their interaction were included as fixed effects. Block and experimental tree nested within block were included as random effects, with the experimental tree treated as the subject of repeated measurements. Before statistical analysis, the data were screened for recording errors and extreme observations. The normality of model residuals was evaluated using the Shapiro–Wilk test and normal quantile–quantile plots, whereas homogeneity of variance was assessed using Levene’s test. When necessary, data were log- or square-root-transformed to satisfy the assumptions of the statistical model. Statistical analyses were performed using the transformed data, while untransformed means were reported to facilitate biological interpretation.

The significance of the main effects of fertilizer placement method and sampling time, as well as their interaction, was evaluated at $p < 0.05$. When a significant treatment $\times$ sampling-time interaction

was detected, the effects of fertilizer placement methods were examined separately within each sampling time. Pairwise comparisons among estimated marginal means were conducted using Tukey's adjustment at the 5% significance level. Results are presented as means $\pm$ standard errors based on six independent replications. Statistical analyses were performed using IBM SPSS Statistics version 26.0.

3. RESULT AND DISCUSSION

3.1 Soil nutrient availability

The initial soil nitrogen (N), phosphorus (P), and potassium (K) values before fertilizer application were 0.20%, 0.18%, and 0.39%, respectively. These baseline values were presented descriptively to characterize the initial nutrient conditions of the experimental soil and were not included as an additional fertilizer placement

treatment. The post-treatment soil nutrient responses under the stake, bracket, and disc methods are presented in [Table 2](#) and [Figure 3](#).

Fertilizer placement method did not significantly affect soil N ($F_{2,10} = 1.262$, $p = 0.324$). Soil N values were $0.190 \pm 0.007\%$, $0.210 \pm 0.008\%$, and $0.200 \pm 0.007\%$ under the stake, bracket, and disc methods, respectively. All treatments belonged to the same DMRT group, indicating that their numerical differences were not statistically significant. The limited response of soil N during the 60-day observation period may reflect the dynamic nature of N in the soil-plant system, including mineralization, immobilization, leaching, root acquisition, and changing plant demand. Nitrogen availability and demand in cacao are also closely associated with plant growth and water use, which may not be fully represented by a single post-treatment soil measurement (Weinstein et al., 2025).

Table 2. Initial and post-treatment soil and cocoa leaf nutrient contents under different fertilizer placement methods

Nutrient parameter	Initial value	Stake	Bracket	Disc	F-value	p-value
Soil nutrients						
Total N (%)	0.20	0.190 ± 0.007^a	0.210 ± 0.008^a	0.200 ± 0.007^a	1.262	0.324
Available P (%)	0.18	2.250 ± 0.053^b	2.230 ± 0.061^b	2.950 ± 0.057^a	36.038	<0.001
Exchangeable K (%)	0.39	1.490 ± 0.041^a	1.450 ± 0.049^a	1.140 ± 0.037^b	14.537	0.001
Leaf nutrients						
Leaf N (% dry matter)	1.58	2.010 ± 0.033^a	1.920 ± 0.029^a	1.950 ± 0.037^a	1.378	0.296
Leaf P (% dry matter)	0.16	0.200 ± 0.006^a	0.180 ± 0.007^a	0.190 ± 0.006^a	1.891	0.201
Leaf K (% dry matter)	1.25	2.140 ± 0.037^a	1.880 ± 0.041^b	1.860 ± 0.033^b	12.816	0.002

In contrast, soil P differed significantly among fertilizer placement methods ($F_{2,10} = 36.038$, $p < 0.001$). The disc method produced the highest soil P value of $2.950 \pm 0.057\%$ and was significantly higher than the stake and bracket methods, which produced values of $2.250 \pm 0.053\%$ and $2.230 \pm 0.061\%$, respectively. The latter two treatments did not differ significantly according to DMRT at the 5% significance level. The continuous circular trench used in the disc method distributed fertilizer across a broader soil area and increased fertilizer–soil contact along the canopy projection. This distribution pattern is particularly relevant for P because of its relatively low mobility and tendency to remain near the application zone through adsorption and precipitation processes (Sutarta et al., 2017; Yazid et al., 2024). Root-zone placement can therefore alter the spatial distribution and persistence of applied nutrients within the soil

surrounding cocoa roots (Meyer zu Drewer et al., 2022).

Soil K was also significantly affected by fertilizer placement method ($F_{2,10} = 14.537$, $p = 0.001$). The stake and bracket methods produced soil K values of $1.490 \pm 0.041\%$ and $1.450 \pm 0.049\%$, respectively, and were statistically comparable. Both values were significantly higher than that produced by the disc method, at $1.140 \pm 0.037\%$. The more localized placement used in the stake and bracket methods may have maintained higher K concentrations within the sampled root-zone soil, whereas the continuous trench used in the disc method may have distributed K across a larger soil volume. Previous studies have similarly indicated that fertilizer placement affects the spatial distribution of nutrients and their accessibility within the root zone (Putri et al., 2022; Meyer zu Drewer et al., 2022).

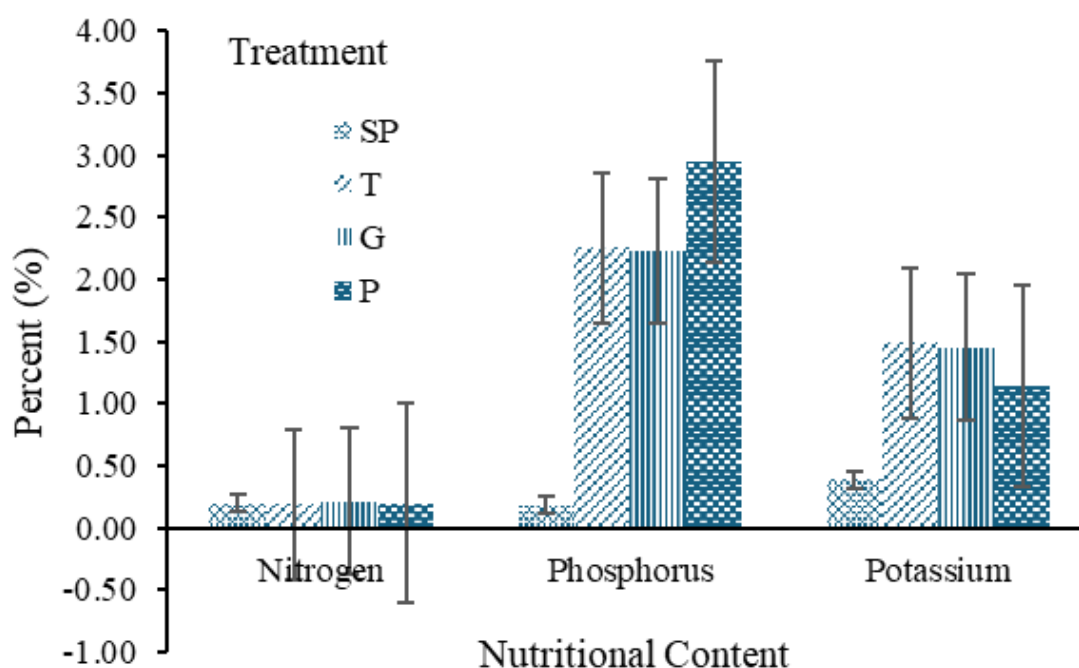


Figure 3. Post-treatment soil nitrogen, phosphorus, and potassium contents under the stake, bracket, and disc fertilizer placement methods. Bars represent means $\pm$ standard error (SE; $n = 6$). Different lowercase letters above bars for the same nutrient indicate significant differences among fertilizer placement methods according to Duncan's multiple range test at $p < 0.05$.

3.2 Cocoa leaf nutrient concentrations

Before fertilizer application, leaf nitrogen (N), phosphorus (P), and potassium (K) concentrations were 1.58%, 0.16%, and 1.25% of leaf dry matter, respectively. These baseline values were used descriptively to characterize the initial nutrient status of the cocoa trees. Fertilizer placement method did not significantly affect leaf N concentration ($F_{2,10} = 1.378$, $p = 0.296$). The stake method produced the numerically highest leaf N concentration at $2.010 \pm 0.033\%$, followed by the disc method at $1.950 \pm 0.037\%$ and the bracket method at $1.920 \pm 0.029\%$. However, all treatments belonged to the same DMRT group, indicating that the observed differences were not statistically significant.

Similar response was observed for leaf P concentration. The effect of fertilizer placement method was not significant ($F_{2,10} = 1.891$, $p = 0.201$), with values of $0.200 \pm 0.006\%$, $0.180 \pm 0.007\%$, and $0.190 \pm 0.006\%$ under the stake, bracket, and disc methods, respectively. Although the stake method produced the highest numerical value, the three placement methods resulted in statistically comparable leaf P concentrations. This finding indicates that the greater soil P concentration observed under the disc method was not accompanied by a proportional increase in leaf P during the 60-day observation period. In contrast, fertilizer placement significantly affected leaf K concentration ($F_{2,10} = 12.816$, $p = 0.002$). The stake method produced the highest leaf K concentration at $2.140 \pm 0.037\%$ and was significantly higher than

the bracket and disc methods, which produced values of $1.880 \pm 0.041\%$ and $1.860 \pm 0.033\%$, respectively (Figure 4). The bracket and disc methods did not differ significantly from each other.

The higher leaf K concentration under the stake method may be associated with the localized placement of fertilizer in several vertical holes within the active root zone. This placement pattern may create nutrient-enriched microsites that increase root access to K and support its subsequent transport to leaf tissues. Studies on cocoa have similarly shown that nutrient responses are influenced by fertilizer placement, nutrient supply, root-zone conditions, and plant developmental stage (Meza-Calderón et al., 2019; Meyer zu Drewer et al., 2022; Mutaqin et al., 2025). Nevertheless, the present study did not measure root proliferation, nutrient fluxes, or total plant nutrient accumulation; therefore, this explanation should be regarded as a plausible mechanism rather than direct evidence of increased nutrient uptake.

Leaf nutrient analysis reflects the integrated nutritional status of the plant and can complement soil analysis when evaluating fertilizer responses (Prado and Rozane, 2020). However, leaf nutrient concentration should not be interpreted as total nutrient uptake or nutrient-use efficiency because plant biomass and whole-plant nutrient accumulation were not measured. Overall, the stake method improved leaf K concentration, whereas its higher numerical leaf N and P values represented tendencies rather than statistically significant advantages.

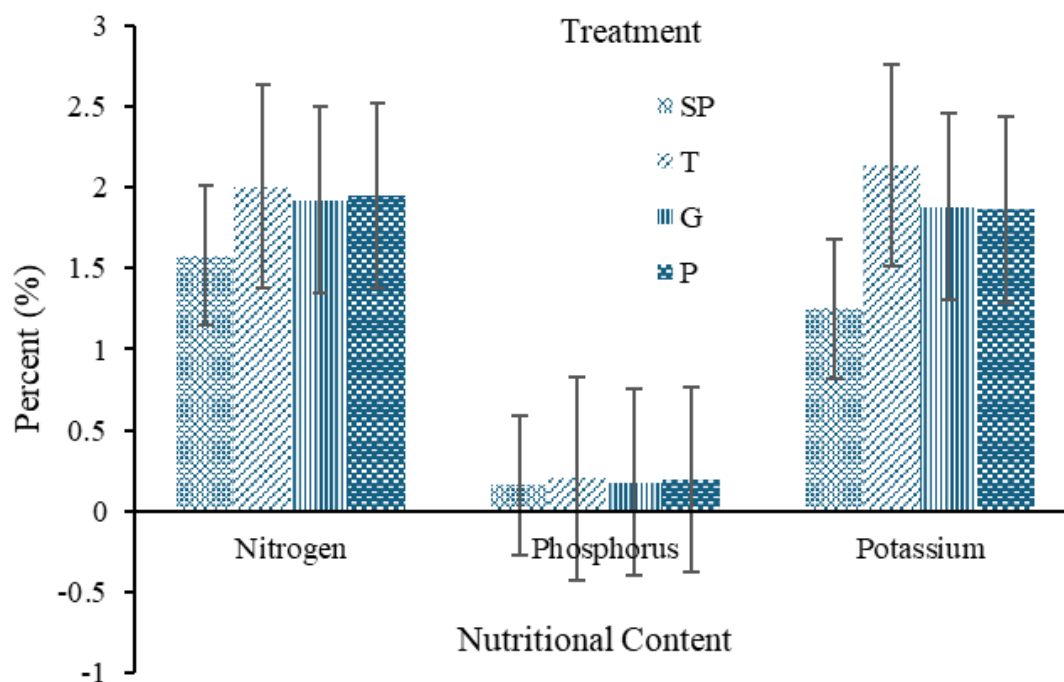


Figure 4. Effects of fertilizer placement method on cocoa leaf nutrient concentrations: (a) nitrogen, (b) phosphorus, and (c) potassium. Bars represent means $\pm$ standard error (SE; $n = 6$). Different lowercase letters above the bars within each panel indicate significant differences among fertilizer placement methods according to Duncan's multiple range test at $p < 0.05$.

3.3 Relationship between soil nutrient availability and cocoa leaf nutrient status

Soil nutrient availability and cocoa leaf nutrient concentrations were related but did not respond proportionally to fertilizer placement methods. The disc method produced the highest soil P value, whereas leaf P concentrations remained statistically comparable among the stake, bracket, and disc methods. Conversely, the stake method produced the highest leaf K concentration and maintained a relatively high soil K value. These contrasting patterns indicate that the amount of a nutrient detected in the soil does not necessarily correspond directly to its concentration in cocoa leaves. The difference between soil and leaf P responses is particularly important. The higher soil P value under the disc method suggests that a greater proportion of P remained extractable within the sampled soil layer. However, the absence of a corresponding

increase in leaf P indicates that soil P availability alone did not determine the short-term nutritional response of the cocoa trees. Nutrient acquisition by perennial plants also depends on the spatial coincidence between active roots and nutrient-enriched soil zones, root interception, nutrient transport across root membranes, internal translocation, and physiological demand. soil N was moderately and negatively correlated with leaf N concentration ($r = -0.569$, $p = 0.014$), whereas soil P showed no relationship with leaf P concentration ($r = 0.007$, $p = 0.979$). In contrast, soil K was positively correlated with leaf K concentration ($r = 0.658$, $p = 0.003$), indicating a more consistent soil–leaf response for K than for N and P. These results support the view that soil nutrient availability does not always produce a proportional response in cocoa leaf nutrient status (Figure 5).

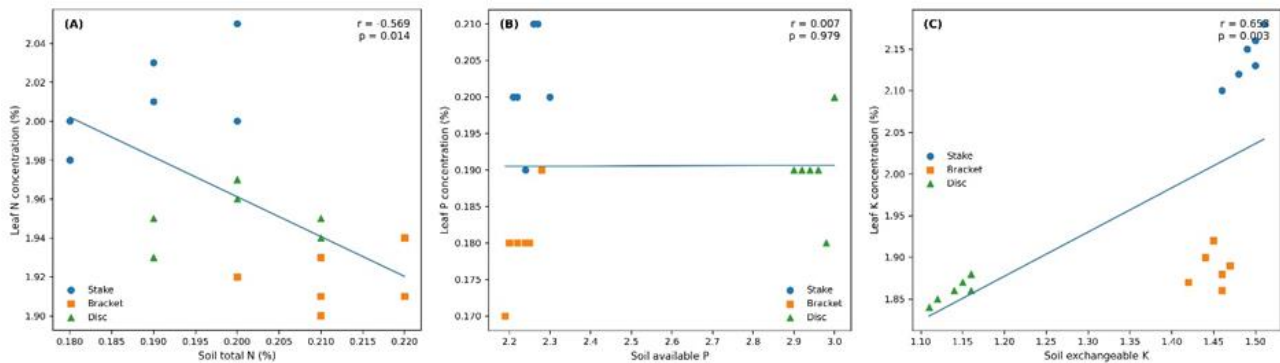


Figure 5. Relationships between post-treatment soil nutrient availability and cocoa leaf nutrient concentrations under different fertilizer placement methods: (A) soil total N and leaf N concentration, (B) soil available P and leaf P concentration, and (C) soil exchangeable K and leaf K concentration. Each point represents one experimental unit ($n = 18$). Different symbols indicate the stake, bracket, and disc fertilizer placement methods. Solid lines represent fitted linear relationships. Pearson's correlation coefficients and associated p -values are presented in each panel.

The stake and bracket methods maintained higher soil K values than the disc method, while the stake method resulted in the significantly highest leaf K concentration. Localized fertilizer placement under the stake method may have positioned K within nutrient-enriched zones accessible to active roots, thereby supporting its movement from the soil to leaf tissues. Nevertheless, leaf K concentration represents plant nutrient status at the time of sampling and does not quantify total K uptake because plant biomass and whole-tree nutrient accumulation were not measured.

Soil and leaf N showed no significant differences among fertilizer placement methods. This limited response may reflect the dynamic behavior of N in the soil-plant system, where mineralization, immobilization, leaching, volatilization, root acquisition, and internal redistribution can occur simultaneously. The 60-day observation period may also have been insufficient to capture longer-term differences in N availability and its accumulation in mature cocoa leaves. The non-proportional responses observed in the present study agree with evidence that soil nutrient measurements and cocoa leaf mineral concentrations may show weak or inconsistent relationships under field conditions (de Abreu Loureiro et al., 2024). Soil analysis primarily

characterizes nutrients that remain extractable within a defined soil layer, whereas leaf analysis integrates root acquisition, internal transport, plant demand, and physiological regulation over time. Therefore, soil and leaf analyses should be interpreted as complementary rather than interchangeable indicators of cocoa nutritional status (Prado and Rozane, 2020).

Overall, fertilizer placement influenced nutrient retention in the soil and nutrient expression in cocoa leaves through different pathways. The higher soil P under the disc method and the higher leaf K under the stake method demonstrate that greater soil nutrient availability does not automatically produce a proportional leaf response. Interpretation of these findings is limited by the absence of measurements of root distribution, soil moisture, nutrient fluxes, plant biomass, and total nutrient accumulation. Longer-term studies incorporating these variables are required to clarify the processes linking fertilizer placement, soil nutrient dynamics, and cocoa plant nutrition.

3.4 Nutrient response mechanisms under different fertilizer placement methods

The contrasting soil and leaf nutrient responses observed among the fertilizer placement methods can be interpreted from differences in fertilizer

distribution, nutrient concentration gradients, fertilizer–soil contact, and proximity to active roots. The stake method concentrated fertilizer in several vertical holes, the bracket method distributed fertilizer within two semicircular trenches, and the disc method placed fertilizer continuously around the canopy projection. These spatial configurations likely created different nutrient-enriched zones within the cocoa root system and consequently affected nutrient retention in the soil and nutrient accessibility to roots.

The stake method created localized zones with relatively high nutrient concentrations. Roots located near these fertilizer-enriched microsites may have had greater access to readily available K, which could explain the higher leaf K concentration recorded under this treatment. Localized fertilizer placement may also stimulate root activity near the application points, although root proliferation was not measured in the present study. Research on root-zone fertilizer application in young cocoa plants similarly demonstrated that the position of fertilizer relative to the root system can influence plant nutritional responses, although the magnitude of the

response depends on fertilizer composition, root development, and growing conditions (Meyer zu Drew et al., 2022).

The bracket method represented an intermediate spatial arrangement between the highly localized stake method and the continuously distributed disc method. Its two semicircular trenches increased the treated soil area while maintaining relatively concentrated fertilizer zones. This configuration may explain why the bracket method maintained soil K values comparable to those under the stake method but did not produce an equally high leaf K concentration. The result suggests that nutrient concentration in the sampled soil alone was insufficient to determine the leaf response, as nutrient acquisition also depended on the distribution and physiological activity of roots within the fertilized zones. The proposed mechanisms underlying the contrasting soil and leaf nutrient responses among the stake, bracket, and disc fertilizer placement methods are conceptually illustrated in [Figure 6](#).

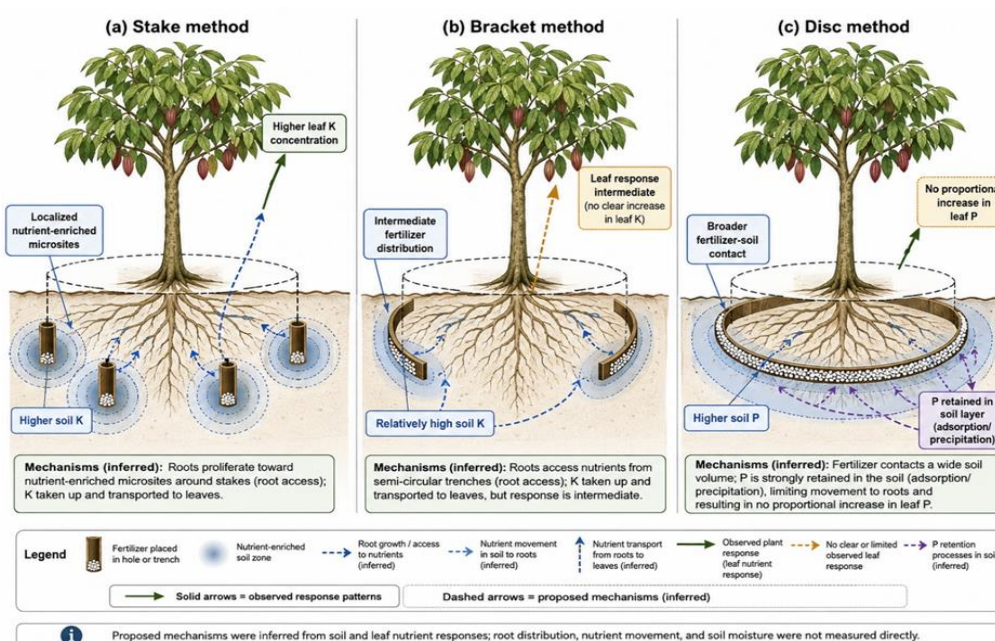


Figure 6. Conceptual illustration of the proposed nutrient-response mechanisms under the stake, bracket, and disc fertilizer placement methods in cocoa

In contrast, the disc method distributed fertilizer over a broader and more continuous soil volume. This arrangement increased fertilizer–soil contact and may have promoted P retention within the sampled layer because P is relatively immobile and readily interacts with soil mineral surfaces. The broader distribution of P may therefore have increased its extractable concentration in the soil without producing a proportional short-term increase in leaf P. A continuous fertilizer band may also reduce nutrient concentration at individual points compared with localized placement, potentially limiting the formation of highly concentrated nutrient microsites accessible to particular root segments.

The differing responses of N, P, and K further indicate that fertilizer placement interacted with the chemical behavior of each nutrient. Soil N remained relatively similar among placement methods, which may be associated with its dynamic transformations and movement within the soil–plant system. By contrast, the stronger soil P response reflected its limited mobility and greater sensitivity to fertilizer–soil contact, whereas the soil and leaf K patterns were more closely associated with the location and concentration of fertilizer within the active root zone. Nutrient requirements in cocoa also change with plant growth, physiological demand, and water availability, which can influence the extent to which soil nutrient differences are expressed in leaf tissues (Weinstein et al., 2025).

These interpretations indicate that no single fertilizer placement method was consistently superior for all measured nutrients. The disc method favored P retention in the sampled soil, whereas the stake method was more closely associated with increased leaf K concentration. The bracket method produced an intermediate response by combining partial spatial coverage with localized fertilizer placement. However, these mechanisms cannot be confirmed solely from soil and leaf nutrient concentrations. Measurements of root-length density, soil moisture, nutrient concentration gradients, P-sorption characteristics, microbial

activity, and total plant nutrient accumulation would be required to determine how fertilizer placement regulates nutrient movement and acquisition in productive cocoa plantations.

3.5 Practical implications and study limitations

The contrasting responses among fertilizer placement methods have practical implications for nutrient management in productive cocoa plantations. The disc method may be considered when the primary objective is to increase or maintain P within the fertilized soil layer, whereas the stake method may be more suitable when the management objective is to improve leaf K status. The bracket method produced an intermediate response, particularly by maintaining soil K concentrations comparable to those under the stake method. These findings indicate that fertilizer placement should be selected according to the target nutrient and the initial soil and plant nutrient conditions rather than assuming that one method will be equally effective for all nutrients.

Soil and leaf analyses should therefore be used jointly when developing fertilizer recommendations. Soil analysis provides information on nutrients remaining or extractable within the root-zone soil, whereas leaf analysis reflects the integrated nutritional status of cocoa trees. Their combined interpretation can help identify whether a fertilizer placement method primarily affects nutrient retention in the soil or nutrient expression in plant tissues (Prado and Rozane, 2020; Loureiro et al., 2024). Periodic soil and leaf testing is particularly important because nutrient demand and fertilizer responses may change with plant growth, water availability, and production stage (Weinstein et al., 2025).

The results do not support identifying a single fertilizer placement method as universally superior. Although the disc method increased soil P and the stake method increased leaf K, these responses were evaluated over only 60 days and were not accompanied by measurements of vegetative growth, cocoa yield, bean quality, or economic return. Consequently, the observed improvements

in soil or leaf nutrient status cannot yet be interpreted as evidence of higher productivity or fertilizer-use efficiency. Labor requirements, application costs, soil disturbance, and the practicality of constructing holes or trenches were also not evaluated and should be considered before recommending a method for large-scale adoption.

Future studies should evaluate fertilizer placement methods across multiple seasons, soil types, cocoa cultivars, and plantation ages. Measurements should include root-length density, soil moisture, nutrient concentration at several distances and depths from the fertilizer-placement zone, plant biomass, total nutrient accumulation, yield, bean quality, labor requirements, and economic return. Combining these variables would provide a stronger basis for determining whether the disc, stake, or bracket method offers the greatest agronomic and economic benefit under specific cocoa-production conditions.

4. CONCLUSION

Fertilizer placement methods produced different responses in soil nutrient availability and cocoa leaf nutrient status during the 60-day observation period. The disc method resulted in the highest soil available P, whereas the stake method produced the highest leaf K concentration and maintained relatively high soil exchangeable K. Fertilizer placement did not significantly affect soil N or leaf N and P concentrations, indicating that no single method was consistently superior for all measured nutrients. For practical nutrient management, cocoa farmers may consider the disc method when increasing P availability in the fertilized soil layer is the primary objective, whereas the stake method may be considered when improving leaf K status is the main concern. The selection of a fertilizer placement method should also consider the target nutrient, initial soil and leaf nutrient conditions, labor requirements, and field feasibility. Periodic soil and leaf analyses are recommended to support site-specific fertilization decisions. These recommendations should be

interpreted cautiously because plant growth, cocoa yield, fertilizer-use efficiency, and economic returns were not evaluated.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Muhammad Husaini Assauwab conceived the research idea, developed the study design, conducted the literature review, coordinated the research activities, analyzed and interpreted the data, and took primary responsibility for writing, revising, and finalizing the manuscript from inception to completion. Rahemi, Patimah, and Anita Dewi contributed substantially to the implementation of the research by assisting in field activities, including plot preparation, fertilizer application, sample collection, field observations, and data recording. All authors participated in discussions of the research findings and approved the final version of the manuscript.

ETHICS APPROVAL

No ethical approval was needed for this study.

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CONFLICT OF INTEREST

The author declares no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available by request.

REFERENCES

- Arévalo-Hernández, C. O., Arévalo-Gardini, E., Farfan, A., Amaringo-Gomez, M., Daymond, A., Zhang, D., & Baligar, V. C. (2022). Growth and Nutritional Responses of Juvenile Wild and Domesticated Cacao Genotypes to Soil Acidity. *Agronomy*, 12(12), 3124. doi:<https://doi.org/10.3390/agronomy12123124>
- Arthur, A., Acquaye, S., Cheng, W., Dogbatse, J. A., Konlan, S., Domfeh, O., & Quaye, A.

- K. (2022). Soil carbon stocks and main nutrients under cocoa plantations of different ages. *Soil Science and Plant Nutrition*, 68(1), 99-103. doi:<https://doi.org/10.1080/00380768.2022.2029219>
- de Abreu Loureiro, G. A. H., Reis de Araujo, Q., Ahnert, D., Morales-Reyes, E. I., Escalona-Valdez, R. A., Mendonça Póvoas, C. E., & Baligar, V. C. (2024). Method of Analysis of the Sample Matching of Diagnostic Ranges of Mineral Nutrients in Soil and Cacao Leaves. *Communications in Soil Science and Plant Analysis*, 55(2), 178-195. doi:<https://doi.org/10.1080/00103624.2023.2265422>
- Espinoza Herrera, R., Vásquez Vásquez, S. S., Seco Granja, F., Molina-Müller, M. L., Capa-Morocho, M., & Cusquillo Guamán, A. L. (2022). Interacción de nitrógeno, fósforo y potasio sobre características del suelo, crecimiento y calidad de brotes y frutos de cacao en la Amazonía Ecuatoriana. *Bioagro-*, 34(3), 277–288. <https://doi.org/10.51372/bioagro343.7>
- Meyer zu Drewer, J., Köster, M., Abdulai, I., Rötter, R. P., Hagemann, N., & Schmidt, H. P. (2022). Impact of Different Methods of Root-Zone Application of Biochar-Based Fertilizers on Young Cocoa Plants: Insights from a Pot-Trial. *Horticulturae*, 8(4), 328. doi:<https://doi.org/10.3390/horticulturae8040328>
- Meza-Calderón, M. A., Moya-Menjívar, X. M., Parada-Berrios, F. A., & Vásquez-Osegueda, E. A. (2019). *Nutrición de portainjertos de cacao (Theobroma Cacao L.) utilizando diferentes dosis de fórmula 15-15-15 y su influencia en el prendimiento de cuatro tipos de injerto*: 2(1), 63–78. <https://minerva.sic.ues.edu.sv/index.php/Minerva/article/download/27/44>
- Rychel, V., Meurer, K. H. E., Getahun, G. T., Bergström, L., Kirchmann, H., & Kätterer, T. (2023). Lysimeter deep N fertilizer placement reduced leaching and improved N use efficiency. *Nutrient Cycling in Agroecosystems*, 126(2), 213–228. doi:10.1007/s10705-023-10286-w
- Murillo Castillo, R. G., Piedra Marín, G., & Leon, R. G. (2013). Absorción de nutrientes a través de la hoja. *Uniciencia*, 27(1), 232–244. <https://dialnet.unirioja.es/servlet/articulo?codigo=4945327>
- Mutaqin, Z., Pratiwi, S. N., Yunita, T. R., Yama, D. I., & Solihin, E. (2025). Efektivitas Beberapa Jenis Pupuk Nitrogen pada Pembibitan Tanaman Kakao (*Theobroma cacao* L.). *Jurnal Ilmiah Universitas Batanghari Jambi*, 25(2), 1151. <https://doi.org/10.33087/jiubj.v25i2.6108>
- Prado, R. de M., & Rozane, D. E. (2020). *Leaf analysis as diagnostic tool for balanced fertilization in tropical fruits* (pp. 131–143). Elsevier. <https://doi.org/10.1016/B978-0-12-818732-6.00011-3>
- Puentes-Páramo, Y. J., Menjivar-Flores, J. C., & Aranzazu-Hernández, F. (2014). *Eficiencias en el uso de nitrógeno, fósforo y potasio en clones de cacao (Theobroma cacao L.)*. 26(2), 99–106. <http://ve.scielo.org/pdf/ba/v26n2/art04.pdf>
- Puspita, V. A., Hamakonda, U. A., Taus, I., & Lea, V. C. (2024). Pelatihan Teknis Budidaya Kakao Guna Peningkatan Produktivitas di Kelurahan Tanah Rata, Kecamatan Kota Komba, Kabupaten Manggarai Timur. *Abdi Unisap*, 2(2), 321–327.

- <https://doi.org/10.59632/abdiunisap.v2i2.334>
- Putri, Z., Lumbanraja, J., Novpriansyah, H., & Utomo, M. (2022). PENGARUH OLAH TANAH DAN PEMUPUKAN TERHADAP PERTUMBUHAN, PRODUKSI, DAN HARA TERANGKUT (C, N, P, K) TANAMAN KACANG HIJAU (*Vigna radiata* L.). *Jurnal Agrotek Tropika*, 10(1), 67–74.
- <https://doi.org/10.23960/jat.v10i1.5631>
- Santosa, B. (2024). UJI BEBERAPA JENIS DAN DOSIS BAHAN ORGANIK TERHADAP PERTUMBUHAN BIBIT KAKAO (*Theobroma cacao* L.). *Jurnal Embrio*, 16(1), 59.
- <https://doi.org/10.31317/embrio.v16i1.1033>
- Sitorus, U. K. P., Siagian, B., & Rahmawati, N. (2014). Respons pertumbuhan bibit kakao (*Theobroma cacao* L.) terhadap pemberian abu boiler dan pupuk urea pada media pembibitan. *Jurnal Online Agroekoteknologi*. ISSN No, 2337, 6597.
- Sutarta, E. S., & Winarna, M. A. Y. Distribusi Hara Dalam Tanah Dan Produksi Akar Tanaman Kelapa Sawit Pada Metode Pemupukan Yang Berbeda. *Jurnal Pertanian Tropik* E-ISSN No, 2356, 4725.
- Schmidt, J. E., Hasan, H., Ward, A., Firl, A. J., & Khalsa, S. D. S. (2025). Tradeoffs among ecosystem services and microbiome impacts associated with two cover crops for cocoa in South Sulawesi, Indonesia. *Agroforestry Systems*, 99(1), 24. doi:10.1007/s10457-024-01098-0
- Timor, P., Agusta, B., Tyasmoro, S. Y., & Sebayang, H. T. (2016). Respon pertumbuhan bibit kakao (*Theobroma cacao* L.) Pada berbagai jenis media tanam *Jurnal Produksi Tanaman*, Volume 4, Nomor 4, April 2016, hlm. 276 - 282.
- Weinstein, M., Graber, E. R., Yermiyahu, U., Sperling, O., Tsehansky, L., Elmakias, A., . . . Baram, S. (2025). Nitrogen Affects Cacao (*Theobroma cacao* L.) Tree Growth, Macronutrient Demand, and Water Use. *Journal of the American Society for Horticultural Science*, 150(5), 290-299.
- doi:<https://doi.org/10.21273/JASHS05518-25>
- Yazid, A. ., Mahyunis, M., Napitu, P. L. ., Simangunsong, S. ., Nurhamdi, M., Imran, A. ., & Nasution, N. M. . (2024). Perawatan Tanaman Kelapa Sawit Di Lahan Masyarakat Desa Bukit Cermin Hilir Kecamatan Dolok Masihul Kabupaten Serdang Bedagai. *IRA Jurnal Pengabdian Kepada Masyarakat (IRAJPKM)*, 2(3), 130–137.
- <https://doi.org/10.56862/irajpkm.v2i3.168>