



Scientia Agropecuaria

Web page: <http://revistas.unitru.edu.pe/index.php/scientiaagrop>

Facultad de Ciencias
Agropecuarias

Universidad Nacional de
Trujillo



RESEARCH ARTICLE

Integrating SEM-PLS and NCA to reveal the mediating role of leaf nutrient status in linking soil nutrient availability and oil palm yield in peatlands

Ireng Darwati¹ ; Muchamad Yusron^{1*} ; Joko Purnomo¹ ; Rudi Suryadi¹ ; Devi Rusmin¹ ; Octivia Trisilawati¹ ; Edi Yatno¹ ; Joko Pitono² ; Nurjaya¹ ; Djajadi¹ ; Muhammad Syakir¹ ; Eni Fidiyawati¹ ; Rr Sri Hartati¹

¹ Research Center for Estate Crops, National Research and Innovation Agency, Indonesia.

² Research Center for Horticulture, National Research and Innovation Agency, Indonesia.

* Corresponding author: yusron1061@gmail.com; much012@brin.go.id (M. Yusron).

Received: 2 June 2025. Accepted: 21 October 2025. Published: 10 November 2025.

Abstract

The expansion of oil palm plantations into peatlands presents a critical area of study, particularly in understanding how nutrient dynamics and groundwater management influence oil palm yield. This research was conducted on smallholder oil palm plantations comprising 8–10-year-old palms cultivated on peat soils in Bengkalis Regency, Riau Province. A completely randomized block design was used, incorporating three groundwater table treatments: A. 40 cm, B. 60 cm, and C. 80 cm. Fertilizer application rates were as follows: urea at 2.50 kg/tree/year, SP-36 at 2.75 kg/tree/year, MOP (KCl) at 2.25 kg/tree/year, and dolomite at 2.00 kg/tree/year. Data analysis utilized a combination of Structural Equation Modeling based on Partial Least Squares (SEM-PLS) and Necessary Condition Analysis (NCA). The results showed that nutrient dynamics, indicated by leaf nutrient content, are the key driver connecting soil nutrient availability with oil palm yield. This finding emphasizes the importance of monitoring and managing nutrient flows through the plant to optimize fertilization strategies and improve yield performance. The combined use of SEM-PLS and NCA provides a robust analytical framework for understanding yield formation and developing nutrient management strategies for oil palm cultivation on peatlands.

Keywords: Groundwater management; nutrient-soil management; peat soil; palm growth; soil chemistry.

DOI: <https://doi.org/10.17268/sci.agropecu.2026.012>

Cite this article:

Darwati, I., Yusron, M., Purnomo, J., Suryadi, R., Rusmin, D., Trisilawati, O., Yatno, E., Pitono, J., Nurjaya, Djajadi, Syakir, M., Fidiyawati, E., & Hartati, R. S (2026). Integrating sem-pls and nca to reveal the mediating role of leaf nutrient status in linking soil nutrient availability and oil palm yield in peatlands. *Scientia Agropecuaria*, 17(1), 165-177.

1. Introduction

Indonesia is the world's largest producer of crude palm oil (CPO). Over the last 30 years, the national oil palm plantation area has grown by an average of 12.30% per year, with the fastest growth occurring in smallholder plantations at a rate of 25.20%. In 2025, the area of oil palm plantations in Indonesia was approximately 16.83 million hectares, with 6.9 million hectares occupied by smallholder plantations (Directorate General of Estate Crops, 2025). Recently, due to increased global demand, palm oil cultivation in Indonesia has been expanded to peatlands.

Most peat soils in Indonesia are classified as ombrogenous peat, which is rich in lignin (Anwar et al., 2004; Hikmatullah & Sukarman, 2014). The fiber fraction is a key physical indicator used to assess the degree of peat decomposition (Sutejo et al., 2017;

Kunarso et al., 2022). A high fiber content indicates a low degree of decomposition, while a low fiber content suggests more advanced decomposition (Kurnain, 2019). Low fiber fractions, often found in areas with perennial vegetation, reflect high decomposition levels. In their natural, undisturbed state, peatlands are characterized by high organic matter, strong acidity, low nutrient levels, and a dominance of macropores that enhance water movement (Kurnianto et al., 2019; Cole et al., 2022; Mohamad et al., 2025).

The depth of the groundwater table strongly influences soil nutrient availability. Numerous studies have highlighted the critical role groundwater levels play in regulating nutrient dynamics in peat soils (Macrae et al., 2013; Bakri et al., 2025). Lowering the water table in peatlands can enhance peat decomposition rates and alter

nutrient availability (Hua-Bing et al., 2025). However, the extent of these effects depends on the specific type of peat soil, which impacts the chemical composition and physicochemical properties of humic acids, thereby influencing overall soil chemistry (Anwar et al., 2004; Szajdak et al., 2020). Kassim & Yaacob (2019) reported that maintaining the water table at a depth of 40 cm led to the highest concentrations of total nitrogen (N) and mineral nitrogen (NH_4^+ and NO_3^-) and exchangeable bases such as potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na). Despite these findings, there is still limited research on the impact of groundwater level management on oil palm cultivation, particularly within Indonesia's peatland ecosystems.

One of the most widely used methods for analyzing causal relationships between latent variables in complex, theory-driven models is Partial Least Squares Structural Equation Modeling (SEM-PLS) (Hair et al., 2022). SEM-PLS offers several advantages, including its ability to handle non-normal data distributions, accommodate small to medium sample sizes, and manage high model complexity (Ramayah et al., 2016; Amora, 2021). This method has been successfully applied in various agronomic studies, yielding robust and reliable results (Pu et al., 2024; Wu et al., 2024). While SEM-PLS identifies sufficient conditions for specific outcomes, Necessary Condition Analysis (NCA) complements it by determining the minimum threshold of a variable required for those outcomes to occur (Dul, 2016; Richter et al., 2020; Troiville et al., 2025). The integration of SEM-PLS and NCA enables a more comprehensive analysis of crop production systems, accounting for both statistical relationships and essential biological constraints that contribute to achieving high yields (Gnanasanjevi et al., 2025). This combined approach enhances decision-making in data-driven nutrient management strategies. This study aimed to investigate the relationship between nutrient dynamics and oil palm yield in peatlands, as influenced by changes in groundwater levels in the peat soils of Bengkalis District, Riau Province, Indonesia.

2. Methodology

Description of the study area

This research was conducted on smallholder oil palm plantations located on peatlands in Sadarjaya Village, Bengkalis Kecil Subdistrict, Bengkalis District, Riau Province, Indonesia, at geographic coordinates 102°3'10.8" E and 1°6'54.0" S. The peat

soil in the study area is classified as hemic in terms of its level of decomposition. The oil palm trees observed in this study were approximately 8 to 10 years old.

Experimental design

The experimental design employed a randomized block design with three levels of groundwater level: (A) 40 cm, (B) 60 cm, and (C) 80 cm, replicated three times, as presented in Figure 1. The experimental plot measured 100 m × 100 m with a spacing of 8 m × 9 m, resulting in 138 trees per hectare. The field experiment was conducted over 2 years. Observation of plant growth and production was conducted on 20 samples per plot, a total of 60 samples per treatment. Soil sampling for nutrient analysis was conducted four times over two years at the beginning and end of the rainy season, 15 samples for each sampling time. Soil samples were analysed for the SEM-PLS and NCA methods. Fertilizers applied are urea, 2.50 kg/tree/year; SP-36, 2.75 g/tree/year; MOP (KCl), 2.25 kg/tree/year; and dolomite, 2.00 kg/tree/year.

The observed parameters included soil N, P, and K levels, leaf N, P, and K concentrations, leaflet numbers, leaflet area, leaflet length, midrib length, fruit bunch length, bunch diameter, and bunch weight. Leaf samples were collected from the 17th midrib, specifically from the middle section of the leaf. Leaf nutrient analysis was conducted using the wet method to determine the total levels of N, P, and K. Soil and leaf samples were collected 30 times to monitor the dynamics of soil nutrients in response to the applied treatments and seasonal variations (rainy and dry seasons). Fresh fruit bunches (FFB) were harvested 2-3 times per month over a 2-year production period, depending on fruit maturity.

Statistical Analysis

The data were analyzed using structural equation modeling partial least squares (SEM-PLS) method, and Necessary Condition Analysis (NCA). In this study, SEM-PLS is used to evaluate the research model in both the outer and inner models. Outer model to assess latent variables, emphasizing the validity and reliability of indicators. The analytical procedure consists of convergent validity, discriminant validity, and construct reliability. NCA is a statistical method used to identify the minimum conditions that must be present for a specific outcome to occur. NCA focuses on whether the absence of a particular variable would prevent the outcome from happening. Figure 2 presents the SEM-PLS framework, illustrating the relationships between observed variables and latent variables.

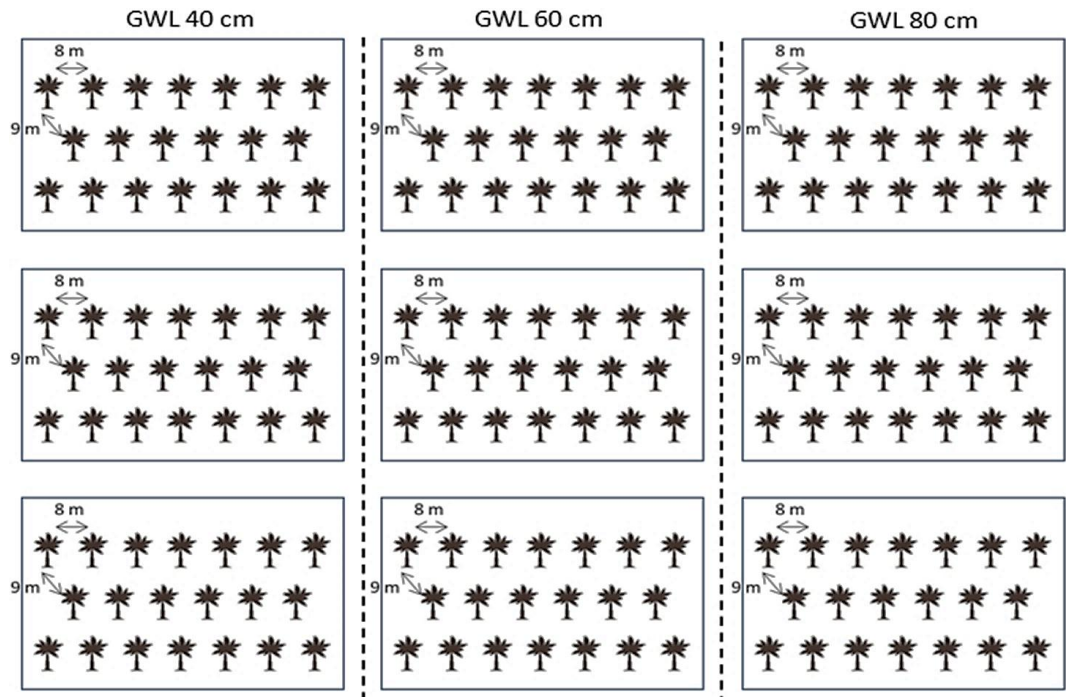


Figure 1. Research experimental design.

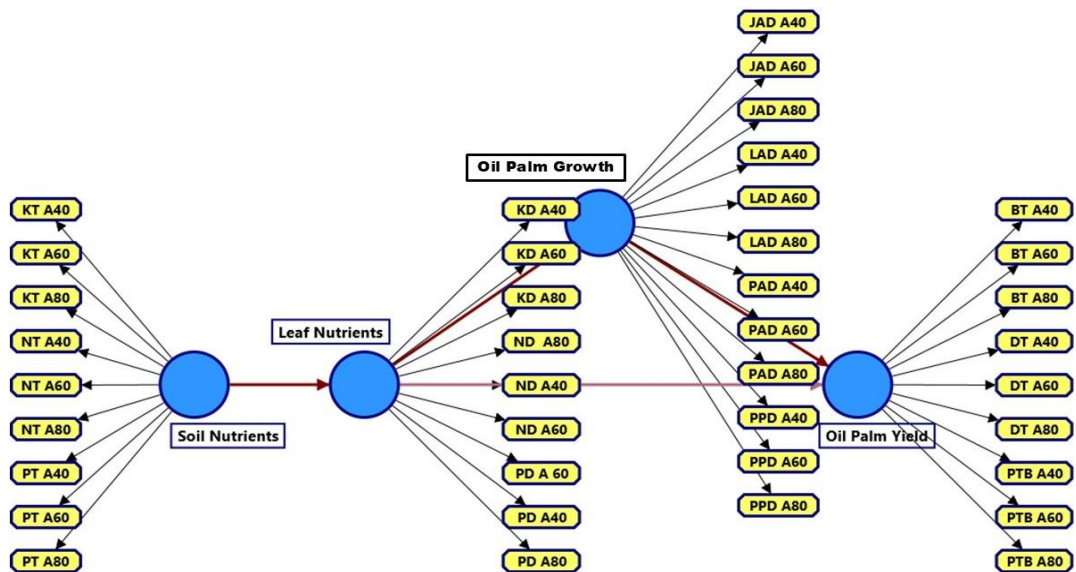


Figure 2. The SEM-PLS framework examines the relationships between observed variables (indicators) and latent variables (constructs). Notes: NT = Soil N; PT = soil P; KT = Soil K; ND = Leaf N; PD = Leaf P; KD = Leaf K; JAD = Leaflet numbers; LAD = Leaflet area; PAD = Leaflet length; PPD = Midrib length; PTB = Fruit bunch length; DT = Bunch diameter; BT = Bunch weight; A40, A60, A80 = groundwater levels (cm).

3. Results and discussion

Peat Soil Characteristics

The peat soil used in this experiment is highly acidic, with a pH of 3.11 in water (pH-H₂O) and 2.58 in KCl (pH-KCl) (Table 1). Due to its origin from organic deposits, the soil contains very high levels of organic carbon (30.6%) and total nitrogen (1.57%). The carbon-to-nitrogen (C/N) ratio is 20, which is relatively high and indicates a low degree of organic

matter decomposition. Although the total nitrogen content is high and fluctuates over time, its availability to plants is limited by the wide C/N ratio (van der Sloot et al., 2022). Nitrogen must typically be supplemented through fertilization to meet plant needs (Zayed et al., 2023). The soil has a very high available phosphorus content (49.9 mg/kg), likely due to organic matter mineralization in peat. It also shows a high cation exchange capacity (120.21 cmol(+)/kg), linked to

elevated organic carbon (30.6%). Despite this, exchangeable bases (Ca, Mg, K, Na) are low to medium (<4% of total cations), while exchangeable aluminum (4.88 cmol(+)/kg) and total iron (1,787 mg/kg) dominate. The soil's very acidic, high Al levels, and low base saturation (4%) contribute to its low fertility. Bulk density is low (0.51 – 0.65 g/cm³) due to high organic matter and increased pore space.

Peat soil nutrient content, particularly N, P, and K, is vital for oil palm growth and yield. While peat has high CEC due to organic acids, its weak adsorption capacity leads to nutrient leaching and high mobility of N, P, and K (Hartatik et al., 2011). Among factors influencing oil palm productivity on peat—such as peat depth, mineral subsoil, and decomposed wood—peat maturity (sapric or hemic) has the greatest impact (Veloo et al., 2015). Groundwater level significantly affects total N, recorded at 1.63%, 1.55%, and 1.60% for water tables at 40, 60, and 80 cm, respectively. This contrasts with findings by Fahmi & Radjaguguk (2013), who reported that lower water tables increase N via enhanced organic matter mineralization (Macrae et al., 2013; Renger et al., 2002). Land use and management affect N and P in the top 0 – 40 cm, with deeper layers remaining stable (Widiarso et al., 2020; Kunarso et al., 2022). Groundwater fluctuations play a key role in regulating peat soil properties.

Structural Equation Modelling (SEM) Partial Least Squares (PLS)

Table 2 and Figure 3 present the reliability and convergent validity of the improved model. The Soil Nutrients construct has an AVE below the recommended threshold (0.414 < 0.5), indicating limited explanatory power; its composite reliability exceeds 0.6, and indicator loadings are adequate (Table 2). Therefore, the construct is retained based on exploratory value and relevance to the study context. Composite Reliability (CR or ρ_c), which serves as a more accurate measure of internal consistency reliability within a factor model (Table 3). While Cronbach's Alpha represents the lower bound, Composite Reliability is considered the upper bound for evaluating internal consistency (Hair et al., 2019). A CR value above 0.6 is generally deemed acceptable for exploratory research.

Discriminant validity was assessed using cross-loading analysis, requiring each indicator to load highest on its respective construct (Hair et al., 2021). All indicators meet this criterion, with bolded values indicating the strongest loadings within their original constructs. This consistency across indicators supports the structural validity of the model, confirms the absence of conceptual multicollinearity (Chin & Newsted, 1998; Fornell & Larcker, 1981), and ensures each construct has a distinct interpretation.

Table 1

Chemical characteristics of peat soil in Bengkalis, Riau, Indonesia

Parameter	Unit	Value	Parameter	Unit	Value
pH-H ₂ O (1:5)		3.11	Exchangeable Cations		
pH-KCl 1 N (1:5)		2.58	Ca	cmol(+)/kg	3.36
Organic C (Walkley & Black)	%	30.6	Mg	cmol(+)/kg	1.62
Total N (Kjeldahl)	%	1.57	K	cmol(+)/kg	0.22
C/N		20	Na	cmol(+)/kg	0.70
Available P ₂ O ₅ (Bray 1)	mg/kg	49.9	Total Cation	cmol(+)/kg	7.42
Exchangeable Al (KCl 1N)	cmol(+)/kg	4.88	Base saturation	%	5.90
Total Fe	mg/kg	1,787	Soil CEC	cmol(+)/kg	120.21

Table 2

The reliability and convergent validity of the improved model with deleted items

Constructs	Items	Outer Loading	Cronbach's	CR	AVE
Leaf Nutrients	ND A80	0.722	0.916	0.935	0.708
	ND A40	0.874			
	ND A60	0.726			
	PD A60	0.909			
	PD A40	0.927			
	PD A80	0.866			
Oil Palm Yield	BT A40	0.912	0.807	0.881	0.718
	BT A60	0.951			
	DT A60	0.646			
Oil Palm Growth	LAD A80	0.717	0.658	0.816	0.598
	PAD A80	0.737			
	PPD A80	0.858			
Soil Nutrients	NT A40	0.680	0.375	0.678	0.414
	NT A60	0.605			
	NT A80	0.642			

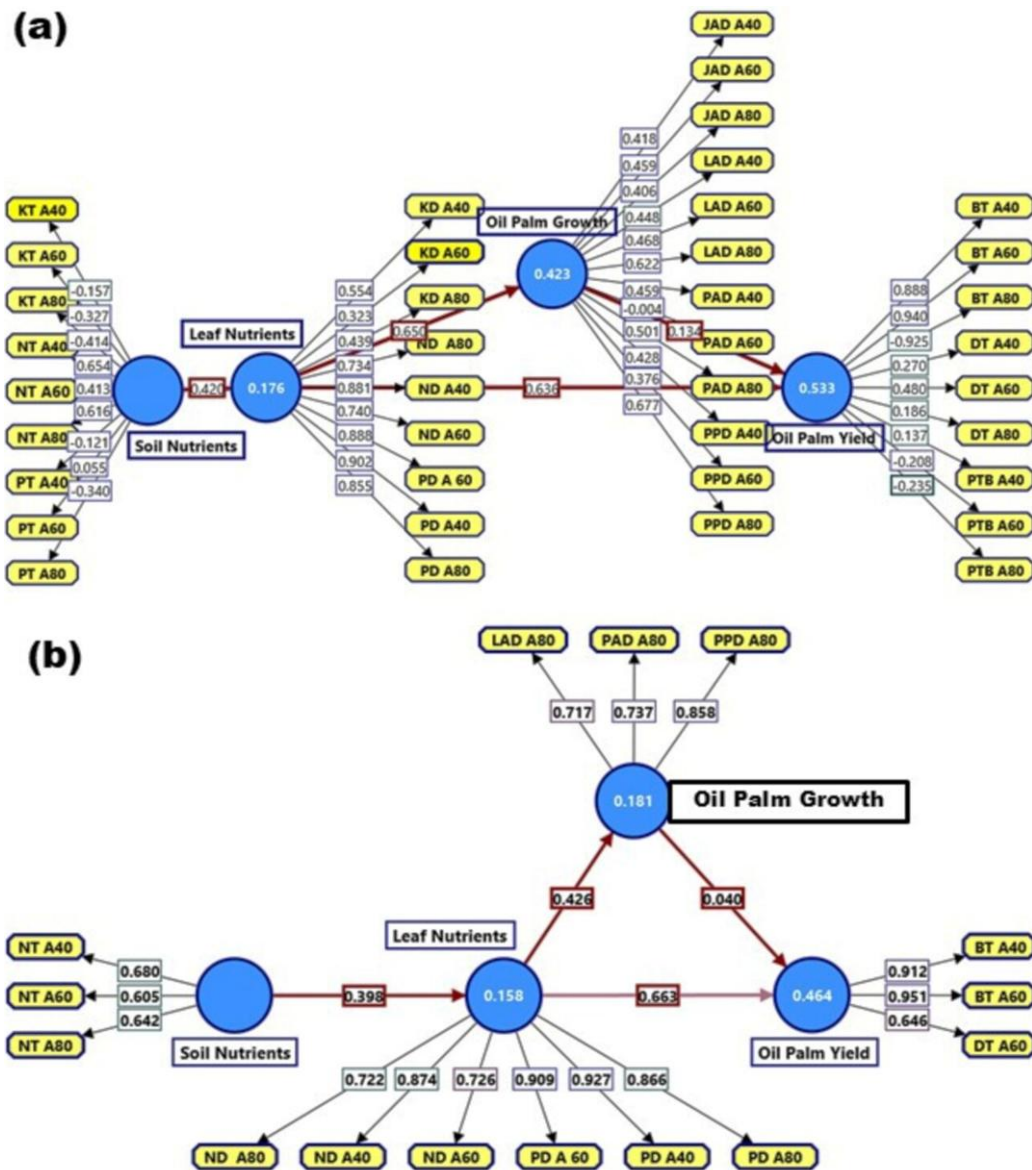


Figure 3. Algorithm of the latent variable model (a) and the improved model (b).

Table 3
The discriminant validity of the revised model

Latent Variable	Fornell-Larcker Criterion			
	Leaf Nutrients	Oil Palm Yield	Oil Palm growth	Soil Nutrients
Leaf Nutrients	1.000			
Oil Palm Yield	0.680	1.000		
Oil Palm Growth	0.426	0.322	1.000	
Soil Nutrients	0.398	0.118	0.171	1.000
Latent Variable	Heterotrait-monotrait ratio (HTMT)			
	Leaf Nutrients	Oil Palm Yield	Oil Palm growth	Soil Nutrients
Leaf Nutrients				
Oil Palm Yield	0.715			
Oil Palm Growth	0.536	0.431		
Soil Nutrients	0.555	0.191	0.618	

Discriminant validity was confirmed using the Fornell–Larcker criterion, which requires the square root of the Average Variance Extracted (AVE) for each construct to exceed its correlations with other constructs (Dijkstra

& Henseler, 2015; Fornell & Larcker, 1981; Hair et al., 2021). As shown in Table 3, all constructs meet this criterion. For example, $\sqrt{\text{AVE}}$ for leaf nutrients is 0.841, higher than its highest correlation (0.680), with similar

results for oil palm yield ($0.847 > 0.680$), growth ($0.773 > 0.426$), and soil nutrients ($0.643 > 0.398$). These results confirm the conceptual distinctiveness of each construct in the model.

Table 3 shows that all HTMT values are below the 0.85 threshold, with the highest being 0.715 between leaf nutrients and oil palm yield. Ranging from 0.191 to 0.618, these values confirm acceptable cross-construct correlations and support the conceptual distinctiveness of each construct in the model. According to (Fornell & Larcker, 1981), discriminant validity is established when a construct's AVE exceeds its correlations with other constructs. **Table 3** confirms this, as each diagonal value (in bold) surpasses the corresponding correlation values. For instance, leaf nutrients (1.000) exceed correlations with oil palm yield (0.680), growth (0.426), and soil nutrients (0.398). These results confirm that all constructs are conceptually distinct, supporting the model's discriminant validity and structural reliability.

Inner model

Table 4 shows that the R^2 value for oil palm yield (0.464) is moderate (Chin, 1998), while leaf nutrients (0.158) and oil palm growth (0.181) are weak. In PLS-SEM, such values remain acceptable for exploratory models (Hair et al., 2021).

Table 4

R^2 Square SEM-PLS of leaf nutrients, oil palm growth, and yield

Constructs	R-square	R-square adjusted	Noted
Leaf Nutrients	0.158	0.144	Very weak
Oil Palm Yield	0.464	0.445	Moderate
Oil Palm Growth	0.181	0.167	Very weak

Noted: R-square value ≥ 0.67 indicates substantial; ≥ 0.33 indicates a moderate; ≥ 0.19 indicates weak (Chin, 1998).

Table 5 indicates that leaf nutrients $\rightarrow$ yield has a strong effect ($f^2 = 0.671$), leaf nutrients $\rightarrow$ growth ($f^2 = 0.221$), and soil nutrients $\rightarrow$ leaf nutrients ($f^2 = 0.188$) are moderate, and growth $\rightarrow$ yield is negligible ($f^2 = 0.002$). These findings emphasize the dominant influence of leaf nutrients on oil palm yield and growth.

Table 6 indicates statistically significant path coefficients (Hair et al., 2021), with bootstrapping confirming both direct and indirect effects.

Table 5

F Square and Path Coefficient Bootstrapping direct effect of constructs

Relationship of constructs	f-square*	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	p-value**
Leaf Nutrients -> Oil Palm Growth	0.221	0.426	0.442	0.101	4.22	0.000
Leaf Nutrients -> Oil Palm Yield	0.671	0.663	0.668	0.078	8.511	0.000
Oil Palm Growth -> Oil Palm Yield	0.002	0.04	0.052	0.136	0.297	0.383
Soil Nutrients -> Leaf Nutrients	0.188	0.398	0.416	0.087	4.555	0.000

* f-square value ≥ 0.02 indicates a weak effect; ≥ 0.15 indicates a moderate effect; ≥ 0.35 indicates a strong effect (Hair et al., 2019). ** p value 0.01; 0.05; 0.10 and T. Sig = 2.58; 1.96; 1.65 (Hair et al., 2019).

Significant direct paths include leaf nutrients $\rightarrow$ oil palm growth ($t = 4.22$, $p = 0.000$), leaf nutrients $\rightarrow$ yield ($t = 8.511$, $p = 0.000$), and soil nutrients $\rightarrow$ leaf nutrients ($t = 4.555$, $p = 0.000$). The path from growth $\rightarrow$ yield is not significant ($t = 0.297$, $p = 0.383$). Indirect effects show significant mediation by leaf nutrients: soil nutrients $\rightarrow$ leaf nutrients $\rightarrow$ yield ($t = 3.642$, $p = 0.000$) and $\rightarrow$ growth ($t = 2.78$, $p = 0.003$). This highlights leaf nutrients as a key mediator linking soil nutrients to plant performance.

Necessary Condition Analysis (NCA)

The multilevel path model (Figure 4) in this study revealed that the effect of soil nutrients on oil palm yield was indirect and weak (total indirect effect = 0.000827). Soil nutrients affect leaf nutrients ($\beta = 0.048$), which in turn affect plant growth ($\beta = 0.123$), and then affect yield ($\beta = 0.140$). Although soil nutrients did not show a direct or dominant effect on yield, their role is still vital in forming a more efficient plant physiological supply chain through their influence on leaf nutrition and growth. These results support the sink-source theory and the physiological efficiency of tropical plants (Hair et al., 2021; Taiz et al., 2015), and provide evidence that interventions at the growth stage have a more significant impact on production yields than direct interventions on leaf or soil nutrition aspects.

Soil Nutrient $\rightarrow$ Leaf Nutrient

The results of the permutation significance test (Table 8) with a value of $p = 0.121$ (CE-FDH) and $p = 0.078$ (CR-FDH), effect size values of 0.048 (CE-FDH) and 0.044 (CR-FDH), indicate that the effect of the necessary condition of soil nutrients is not statistically significant and cannot be considered a significant necessary condition for achieving maximum oil palm yields. The effect size (d) in NCA represents the size of the ceiling zone, the area in which outcomes are impossible without certain conditions being met. Since the effect sizes for soil_nutrients are below 0.1, they are too small to qualify as strong necessary conditions. Therefore, soil nutrients are more appropriately regarded as enabling conditions rather than essential prerequisites in the oil palm production system.

The CE-FDH method yields an accuracy of 100% (Table 7), meaning all data points fall below the ceiling line. It may indicate overfitting due to the method's highly flexible non-parametric nature. In comparison, the CR-FDH method achieves 90% accuracy, which remains robust. CR-FDH is generally considered more conservative and realistic, as it models the ceiling using linear regression (Dul, 2020). The ceiling line in CR-FDH has a slope of 0.795 and an intercept of 0.002. The steep slope reflects a strong positive relationship between soil nutrients and yield. The near-zero intercept suggests that yield approaches zero when soil nutrients are absent, which aligns with the biological reality that nutrient deficiency severely limits oil palm productivity.

Leaf_nutrients, with complete ceiling data (0–100%), is a more stable predictor than soil_nutrients. NCA quantile analysis shows that at high yield levels ($\geq 90\%$), minimum required values for soil and leaf nutrients are 1.740 and 1.382, respectively, highlighting their role as lower-bound conditions for high productivity. This supports the physiological principle that nutrient sufficiency becomes limiting near a plant's genetic yield potential (Taiz et al., 2015) and underscores the value of ceiling-based NCA in identifying productivity bottlenecks (Dul, 2016; Hair et al., 2022). It also aligns with the sink-source concept and rising nutrient demands with increased yield (Kong & Li, 2025; Smith et al., 2018; Taiz et al., 2015).

The leaf nutrient distribution has a mean of 0.987 and a low standard deviation ($SD = 0.183$) with

positive skewness (0.942), as presented in Table 8, meaning that most leaf nutrient values are on the lower side of the distribution, indicating that many plants have not met the minimum threshold value to achieve high growth. This result strengthens the idea that a small increase in leaf nutrients can move the system into a feasible zone of high growth, according to the sink-source model of plant physiology (Bera et al., 2022).

Leaf nutrients can be classified as moderate requirements, the minimum constraints in increasing oil palm growth, although their statistical effects are still marginal. The Cramér–von Mises test shows a p-value < 0.001 for leaf nutrients, indicating that the distribution is significantly different from the normal random distribution — this is valid for using NCA because it does not rely on the normality assumption.

Leaf Nutrient → Oil Palm Growth

Table 9 shows that leaf nutrients are a significant necessary condition for oil palm growth, with an effect size of 0.145 (CR-FDH) and 0.123 (CE-FDH). This value is included in the small to medium effect category; but substantively shows the role of a relevant physiological bottleneck (Richter et al., 2020; Teh et al., 2024). The permutation test (Table 11) produces a p-value = 0.100 (CR-FDH) and 0.148 (CE-FDH), indicating that although it has not reached the conventional significance threshold ($p < 0.05$), it can still be considered theoretically and practically because it is supported by the accuracy of the CR-FDH accuracy model = 90.667%.

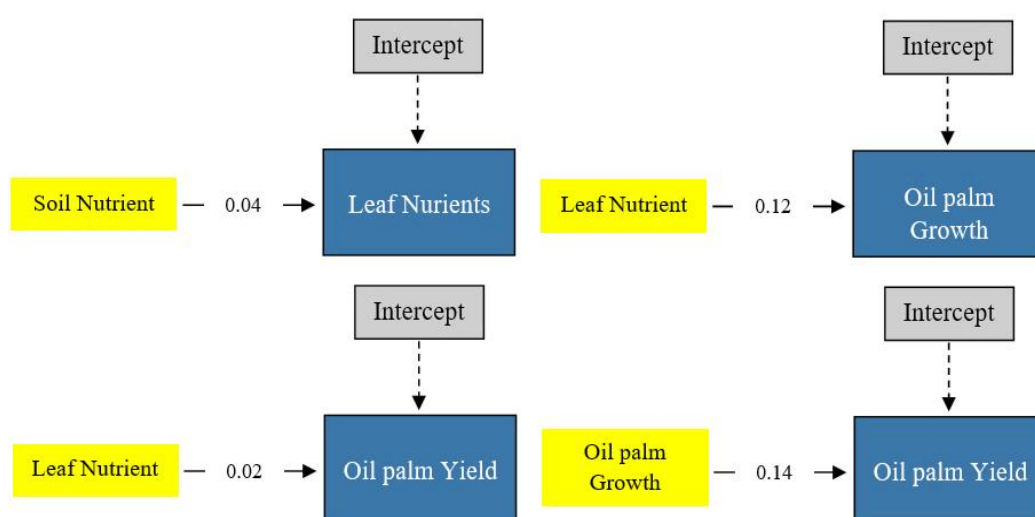


Figure 4. Multilevel path model on the oil palm variable.

Table 6
Path Coefficient Bootstrapping Indirect effect of constructs

Relationship of Constructs	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O /STDEV)	p-value	Noted
Soil Nutrients -> Leaf Nutrients -> Oil Palm growth -> Oil Palm Yield	0.007	0.009	0.027	0.257	0.399	Not Proven
Soil Nutrients -> Leaf Nutrients -> Oil Palm Yield	0.264	0.279	0.072	3.642	0.000	Proven
Soil Nutrients -> Leaf Nutrients -> Oil Palm growth	0.169	0.185	0.061	2.78	0.003	Proven
Leaf Nutrients -> Oil Palm growth -> Oil Palm Yield	0.017	0.024	0.062	0.276	0.391	Not proven

Table 7
Soil nutrient CE-FDH and CR-FDH ceiling line detail

CE-FDH									
p value	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
0.121	0.048	0.000	100.000	n/a	n/a	89.661	35.925	93.376	3.743
CR-FDH									
p value	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
0.078	0.044	6.000	90.000	0.795	0.002	88.134	25.947	91.212	3.656

Table 8
Descriptive soil nutrient to leaf nutrient

Matrix	Mean	Median	Observed min	Observed max	Standard deviation	Excess kurtosis	Skewness	Number of observations used	Cramér-von Mises test statistic	Cramér-von Mises p value
Intercept	0.000	0.000	0.000	0.000	0.000	n/a	n/a	60.000	5.000	0.000
Leaf_Nutrients	0.987	0.931	0.739	1.453	0.183	-0.277	0.942	60.000	0.580	0.000
Soil_Nutrients	1.835	1.607	1.160	6.770	1.027	16.332	4.145	60.000	3.046	0.000

Table 9
Leaf nutrient CE-FDH and CR-FDH ceiling line detail

CE-FDH									
p value	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
0.148	0.123	0.000	100.000	n/a	n/a	44.012	33.954	63.922	23.413
CR-FDH									
p value	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
0.100	0.145	2.000	90.667	77.546	121.991	47.816	44.401	70.987	26.372

The CE-FDH model is more permissive because it does not assume a regression line. Furthermore, leaf nutrients are a significant necessary condition for oil palm growth, with effect sizes of 0.145 (CR-FDH) and 0.123 (CE-FDH) in **Table 11**. These values are included in the small to medium effect category; but substantively indicate a relevant physiological bottleneck role (Richter et al., 2020). The slope of 77.546 and the intercept of 121.991 support the steep slope of the ceiling line, indicating that adding leaf nutrients will quickly lead to maximum outcomes. The condition inefficiency (47.816) and yield inefficiency (44.401) indicate that the system has not reached optimal efficiency, reinforcing that leaf nutrient limits the achievement of maximum growth potential.

Descriptive statistics of leaf nutrient to oil palm growth (**Table 10**) show that the leaf nutrient variable has an average of 0.987 with a standard deviation of 0.183, and a positive skewness of 0.942, indicating a distribution that is skewed to the right (more low values). Meanwhile, the oil palm growth variable averages 179.43 and has a standard deviation of 9.993, with a more symmetrical distribution (skewness 0.305). The results of the Cramér-von Mises test show that the leaf nutrient distribution is significantly different from the random distribution ($p < 0.001$), while the oil palm growth distribution is not significantly different from the random distribution ($p = 0.558$). This value supports the assumption in NCA that the predictor (Leaf Nutrient) is not normally distributed and is valid for ceiling analysis. The outcome, oil palm growth, is evenly distributed.

Oil Palm Growth → Oil Palm Yield

NCA analysis of the relationship between oil palm growth and oil palm yield produces effect size values of 0.140 (CE-FDH) and 0.115 (CR-FDH) (**Table 11**), which are theoretically classified as necessary conditions with small to medium strength (Richter et al., 2020). Although the results of the permutation test $p > 0.05$ indicate that the effect is not statistically significant, the accuracy of the ceiling model is relatively high (100% for CE-FDH and 96.667% for CR-FDH), so it can still be considered in the theoretical framework as a yield limiter. The system efficiency also showed limitations, with the condition inefficiency value reaching 64.486 and the outcome inefficiency of 51.329 in CE-FDH (**Table 11**). This value shows that suboptimal vegetative growth can be a physiological limiting factor for harvest yields, although its contribution is not dominant in the overall system.

Descriptive statistics (**Table 12**) show that the data distribution for both variables is relatively normal and symmetrical (skewness <1), and the results of the Cramér-von Mises test $p > 0.05$ on oil palm yield, indicating no significant deviation from the random distribution and NCA's minimum requirements for data distribution (Dul, 2020).

Leaf Nutrient → Oil Palm Yield

The NCA results show that leaf nutrients are not a statistically significant requirement for oil palm yield, with a small effect size value of 0.024 (CE-FDH) and 0.012 (CR-FDH) (**Table 13**). The permutation results' p-values are far from significant ($p = 0.913$ and 0.930), confirming that leaf nutrients cannot be considered a bottleneck in achieving high yields in palm oil.

The accuracy of the ceiling model is relatively high (98–100%); but because the ceiling zone is very small, its functional interpretation is limited. The ceiling line in the NCA Figure shows that only at yields $>90\%$, does leaf nutrient have a minimum threshold of around 0.841. Still, the number of observations below the ceiling line is only 12 out of 60, which is too small to support the bottleneck model's stability substantially.

Descriptive statistics (**Table 14**) show that leaf nutrient data have a narrow distribution ($SD = 0.183$) and positive skewness (0.942), while oil palm yield data tend to be symmetrical. The Cramér-von Mises test yields $p = 0.000$ for leaf nutrient, indicating that its distribution is not random, making it suitable for testing in the NCA approach. However, NCA found no strong ceiling effect; Leaf nutrient is more appropriately categorized as a supporting factor in the palm oil production system than an absolute requirement.

NCA Ceiling Lines

Figure 5 presents ceiling line charts from the NCA showing relationships between predictors and outcomes: (a) soil nutrients → leaf nutrients, (b) leaf nutrients → growth, (c) growth → yield, and (d) leaf nutrients → yield. Blue dots represent 60 observations; yellow (CE-FDH) and gray (CR-FDH) zones mark infeasible areas. Most data points fall below the ceiling lines, with few or none above, indicating soil nutrients may limit leaf nutrient levels (**Figure 5a**). In **Figure 5b**, leaf nutrient values below the threshold prevent maximum growth, suggesting leaf nutrients are a partial necessary condition for high growth ($\geq 90\%$ yield levels).

Table 10
Descriptive leaf nutrients for oil palm growth

Matrix	Mean	Median	Observed min	Observed max	Standard deviation	Excess kurtosis	Skewness	Number of observations used	Cramér-von Mises test statistic	Cramér-von Mises p value
Intercept	0.000	0.000	0.000	0.000	0.000	n/a	n/a	60.000	5.000	0.000
Leaf nutrient	0.987	0.931	0.739	1.453	0.183	-0.277	0.942	60.000	0.580	0.000
Oil palm growth	179.432	178.321	155.800	207.799	9.993	0.668	0.305	60.000	0.046	0.558

Table 11
Oil palm growth CE-FDH and CR-FDH ceiling line detail

CE-FDH									
	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
Oil palm growth	0.140	0.000	100.000	n/a	n/a	64.486	51.329	82.715	726.217
CR-FDH									
	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
Oil palm growth	0.115	2.000	96.667	0.388	-13.787	56.171	47.575	77.023	676.237

Table 12
Descriptive oil palm growth to oil palm yield

Matrix	Mean	Median	Observed min	Observed max	Standard deviation	Excess kurtosis	Skewness	Number of observations used	Cramér-von Mises test statistic	Cramér-von Mises p value
Intercept	0.000	0.000	0.000	n/a	n/a	60.000	5.000	0.000	0.000	0.000
Oil Palm Growth	155.800	207.799	9.993	0.668	0.305	60.000	0.046	0.558	155.800	207.799
Oil Palm Yields	38.691	55.576	3.510	-0.268	0.149	60.000	0.027	0.881	38.691	55.576

Table 13
Leaf nutrient CE-FDH and CR-FDH ceiling line detail

CE-FDH									
p value	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
0.913	0.024	0.000	100.000	n/a	n/a	85.692	83.153	97.590	11.772
CR-FDH									
p value	Effect size	Obs. above ceiling	Accuracy	Slope	Intercept	Condition inefficiency	Outcome inefficiency	Rel. inefficiency	Abs. inefficiency
0.930	0.012	1.000	98.333	27.826	32.171	85.692	83.153	97.590	11.772

Table 14

Descriptive leaf nutrients to oil palm yield

Matrix	Mean	Median	Observed min	Observed max	Standard deviation	Excess kurtosis	Skewness	Number of observations used	Cramér-von Mises test statistic	Cramér-von Mises p value
Intercept	0.000	0.000	0.000	0.000	0.000	n/a	n/a	60.000	5.000	0.000
Leaf Nutrient	0.987	0.931	0.739	1.453	0.183	-0.277	0.942	60.000	0.580	0.000
Oil Palm Yields	46.833	46.797	38.691	55.576	3.510	-0.268	0.149	60.000	0.027	0.881

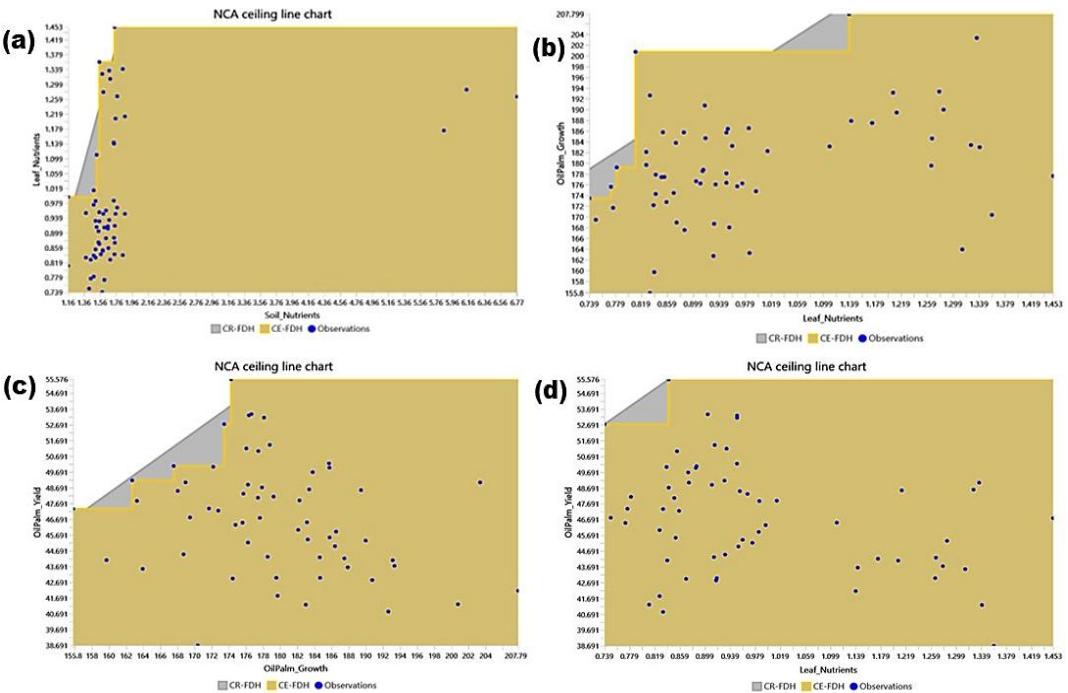


Figure 5. Figure 5. NCA Ceiling Line Chart relationship using the CE-FDH and CR-FDH approaches: (a) Soil Nutrient and Leaf Nutrients, (b) Leaf Nutrients and Oil Palm Growth, (c) Oil Palm Growth and Oil Palm Yield, (d) Leaf Nutrient and Oil Palm Yield.

Further analysis shows that leaf nutrients are not a consistent limiting factor for yield, as most yield levels are achieved without exceeding specific leaf nutrient thresholds (Figure 5c). The shallow slope of the CE-FDH and CR-FDH lines indicates a weak relationship between leaf nutrients and yield. Although a potential ceiling appears above yields of 53.8 (90% – 100% percentile), the limited data points make it insufficient to confirm a bottleneck. The broad distribution below the ceiling line supports earlier findings that leaf nutrients are not a significant necessary condition for oil palm yield.

The multilevel path model shows that soil_nutrients have no direct effect on oil palm yield; but influences it indirectly via leaf nutrients and growth, with a total indirect effect of 0.000827. NCA results (CE-FDH and CR-FDH) show very small, non-significant effect sizes (0.048 and 0.044), indicating soil_nutrients is not a necessary condition. While CE-FDH has 100% accuracy, it risks overfitting; CR-FDH's 90% accuracy offers a more realistic assessment.

In contrast, leaf_nutrient is a significant necessary condition for oil palm growth, with effect sizes of 0.145 (CR-FDH) and 0.123 (CE-FDH), and a p-value near the significance threshold. The growth → yield path shows small to medium effect sizes (0.140 and 0.115) with high model accuracy (>96%). In contrast, the leaf nutrient → yield path has very small, insignificant effect sizes (0.024 and 0.012). Data for leaf and soil nutrients are non-normal and not ideal for NCA, while oil palm yield shows a more symmetrical distribution. These results show that while soil nutrients aren't direct bottlenecks, they are physiologically important in early growth. Leaf nutrients act as a lower-limit requirement for vegetative growth, which drives yield, aligning with the sink-source theory. At the yield stage, only growth functions as a constraint, not leaf or soil nutrients directly, highlighting the need for intervention during the growth phase. NCA reveals critical constraints missed by standard causal analysis. Though some variables lack statistical significance, they remain strategically important as enabling conditions.

4. Conclusions

The results demonstrate that higher soil nutrient availability does not directly enhance oil palm yield; instead, productivity is largely governed by leaf nutrient status, which mediates the relationship between soil fertility and plant performance. Leaf nutrition can be improved through integrated interventions, including soil fertility optimization, enhanced nutrient uptake efficiency, foliar nutrient application, and improved field management. The integration of SEM-PLS and NCA proved essential for disentangling the causal and necessary pathways among soil, leaf, and yield parameters, providing a more comprehensive understanding of nutrient dynamics in peat-based oil palm systems. To strengthen the findings of this study, future research should focus on validating these relationships across different soil types and plantation ages, incorporating temporal (seasonal) data to capture dynamic nutrient interactions. Further research could also integrate physiological and molecular analyses to elucidate the mechanisms regulating nutrient transport and utilization, as well as apply SEM-PLS and NCA frameworks to evaluate the effectiveness of targeted nutrient management strategies in improving yield sustainability.

Acknowledgment

The authors would like to express their sincere gratitude to the Ministry of Agriculture, Republic of Indonesia, for supporting and funding this research. We also wish to thank the Research Organization for Agriculture and Food for their valuable support.

Conflict of Interest

None of the authors has any conflict of interest in this research.

Authors contribution

I. Darwati: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing-original draft, writing-review & editing, visualization, supervision, and project administration. **M. Yusron:** conceptualization, methodology, validation, formal analysis, investigation, data curation, writing-original draft, writing-review & editing, visualization. **J. Purnomo:** methodology, investigation, writing-review & editing. **R. Suryadi:** methodology, validation, writing-original draft, writing-review & editing. **D. Rusmin:** methodology, formal analysis, investigation, writing-original draft, writing-review & editing. **O. Trisilawati:** investigation, writing-original draft, writing-review & editing. **E. Yatno:** investigation, writing-original draft, writing-review & editing. **J. Pitono:** conceptualization, methodology, validation, investigation, writing-review & editing, supervision, and project administration. **Nurjaya:** investigation, writing-original draft. **Djajadi:** investigation, data curation, writing-original draft, writing-review & editing. **M. Syakir:** conceptualization, investigation, supervision, and project administration. **E. Fidiyawati:** methodology, software, validation, formal analysis, writing-original draft, writing-review & editing, visualization, and project administration. **Rr Sri Hartati:** methodology, validation, formal analysis, visualization, writing-review & editing.

ORCID

I. Darwati  <https://orcid.org/0000-0002-4861-9051>
 M. Yusron  <https://orcid.org/0000-0003-4561-9379>
 J. Purnomo  <https://orcid.org/0009-0001-0523-7328>
 R. Suryadi  <https://orcid.org/0000-0002-4990-3150>
 D. Rusmin  <https://orcid.org/0000-0002-8661-1026>
 O. Trisilawati  <https://orcid.org/0000-0002-2753-5289>
 E. Yatno  <https://orcid.org/0000-0002-4501-4305>
 J. Pitono  <https://orcid.org/0000-0003-4967-077X>
 Nurjaya  <https://orcid.org/0009-0000-6824-1992>
 Djajadi  <https://orcid.org/0000-0003-0931-4519>
 M. Syakir  <https://orcid.org/0000-0002-8185-8783>
 E. Fidiyawati  <https://orcid.org/0000-0001-6939-5264>
 Rr Sri Hartati  <https://orcid.org/0000-0003-4127-5564>

References

- Amora, J. T. (2021). Convergent validity assessment in PLS-SEM: A loadings-driven approach. *Data Anal. Perspect. J.*, 2(1), 1–6.
- Anwar, S., Kosaki, T., & Yonebayashi, K. (2004). Cupric oxide oxidation products of tropical peat soils. *Soil Sci. Plant Nutr.*, 50(1), 35–43. <https://doi.org/10.1080/00380768.2004.10408450>
- Bakri Imanudin, M. S., Prayitno, M. B., et al. (2025). Nutrient dynamics in peat soil application under water management planning: A case study of Perigi, South Sumatra, Indonesia. *J. Ecol. Engin.*, 26(6), 162–169. <https://doi.org/10.12911/22998993/202347>
- Bera, A., Sow, S., Ranjan, S., & Murmu, J. (2022). An Overview of the Source-Sink Relationship. *Indian J. Nat. Sci.*, 13(72), 44216–44228.
- Chin, W. W. (1998). Issues and opinions on structural equation modeling. *MIS Quarterly: Management Information Systems*, 22(1).
- Chin, W. W., & Newsted, P. R. (1998). The partial least squares approach to structural equation modeling. Modern methods for business research. *Stat. Strateg. for Small Sample Res.* 295–336.
- Cole, L. E. S., Åkesson, C. M., Hapsari, K. A., .. et al. (2022). Tropical peatlands in the Anthropocene: Lessons from the past. *Anthropocene*, 37(February 2021), 100324. <https://doi.org/10.1016/j.ancene.2022.100324>
- Dijkstra, T. K., & Henseler, J. (2015). Consistent and asymptotically normal PLS estimators for linear structural equations. *Comput. Stat. Data Anal.*, 81, 10–23. <https://doi.org/10.1016/j.csda.2014.07.008>
- Directorate General of Estate Crops. (2025). Statistik Perkebunan Unggulan Nasional Statistics of Estate Crops 2023–2025. In the *Directorate General of Estate Crops, Ministry of Agriculture*.
- Dul, J. (2016). Necessary Condition Analysis (NCA): Logic and Methodology of “Necessary but Not Sufficient” Causality. *Organ. Res. Methods*, 19(1), 10–52. <https://doi.org/10.1177/1094428115584005>
- Dul, J. (2020). How to sample in necessary condition analysis (NCA). *Eur. J. Int. Manag.*, 23(1), 1–13.
- Fahmi, A., & Radjaguguk, B. (2013). Peran Gambut Terhadap Nitrogen Total Tanah di Lahan Rawa (The Role of Peat on Total Nitrogen in The Wetland Soils). *Berita Biologi*, 12(2), 223–230. (in Indonesian)
- Fornell, C., & Larcker, D. F. (1981). Erratum: Structural equation models with unobservable variables and measurement error: Algebra and statistics. *J. Mark. Res.* 18(4), 427. <https://doi.org/10.2307/3150980>
- Gnanasanjevi, G. Balasubramanian, P., Sriram, N., et al. (2025). A PLS-SEM approach to understanding tea growers' adoption intentions of agroforestry boundary planting: an integrated theoretical framework. *Agroforest Syst.*, 99, 99. <https://doi.org/10.1007/s10457-025-01189-6>

- Hartatik, W., Subiksa, I. G. M., & Dariah, A. (2011). Sifat Fisika dan Kimia Lahan Gambut. In *Pengelolaan Lahan Gambut Berkelanjutan* (1st ed., p. 16). <https://doi.org/10.21082/jsdl.v16n1.2022.9-21>
- Hair, J. F., Hult, G. T. M., Ringle, C. M., et al. (2022). A Primer on Partial Least Squares Structural Equation Modeling. *Long Range Planning*, 46(1–2), 184–185. <https://doi.org/10.1016/j.lrp.2013.01.002>
- Hair, J. F., Hult, G. T. M., Ringle, C. M., et al. (2021). *Evaluation of Formative Measurement Models*. In Partial least squares structural equation modeling (PLS-SEM) using R: A workbook (pp. 91–113). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-80519-7_5
- Hair, J. F., Risher, J. J., Sarstedt, M., et al. (2019). When to use and how to report the results of PLS-SEM. *Eur. Bus. Rev.* 31(1), 2–24. <https://doi.org/10.1108/eb-11-2018-0203>
- Hikmatullah & Sukarman (2014). Physical and chemical properties of cultivated peat soils in four trials. *J Trop Soil*, 19(3), 131–141. <https://doi.org/10.5400/jts.2014.v19i3.131-141>
- Hua-Bing, L., Jun-Qin, G., Jia-Tao, Z., et al. (2025). Water table decline reduces soil organic carbon by decreasing particulate organic carbon in peatlands: Beyond enzymic and mineral protection. *CATENA*, 259, 109347. <https://doi.org/10.1016/j.catena.2025.109347>
- Kassim, N. Q. B., & Yaacob, A. (2019). Nutrient Dynamics in Peat Soil: Influence of Fluctuating Water Table. *IOP Conference Series: Earth and Environmental Science*, 327(1). <https://doi.org/10.1088/1755-1315/327/1/012024>
- Kong, J., & Li, Y. (2025). Spatio-temporal variations in carbon sources, sinks, and footprints of cropland ecosystems in the Middle and Lower Yangtze River Plain of China, 2013–2022. *Sci. Rep.*, 15(1), 1–27. <https://doi.org/10.1038/s41598-025-98457-3>
- Kunarso, A., Bonner, M. T. L., Blanch, E. W., et al. (2022). Differences in tropical peat soil physical and chemical properties under different land uses: A Systematic review and meta-analysis. *J. of Soil Sci. and Plant Nutr.*, 22(4), 4063–4083. <https://doi.org/10.1007/s42729-022-01008-2>
- Kurnain, A. (2019). Hydrophysical properties of ombrotrophic peat under drained peatlands. *Int. Agrophys.*, 33(3), 277–283. <https://doi.org/10.31545/intagr/110773>
- Kurnianto, S., Selker, J., Boone Kauffman, J., et al. (2019). The influence of land-cover changes on the variability of saturated hydraulic conductivity in tropical peatlands. *Mitigation and Adaptation Strategies for Global Change*, 24(4), 535–555. <https://doi.org/10.1007/s11027-018-9802-3>
- Macrae, M. L., Devito, K. J., Strack, M., et al. (2013). Effect of water table drawdown on peatland nutrient dynamics: Implications for climate change. *Biogeochemistry*, 112(1–3), 661–676. <https://doi.org/10.1007/s10533-012-9730-3>
- Mohamad, H., Sulaiman, M., Saida, N., et al. (2025). Klias peat soil: a depth-based property assessment. *J. Soil Agric.*, 3(1), 9–28. <https://doi.org/10.37934/sea.3.1.928a>
- Pu, Y., Lang, S., Li, Y., et al. (2024). Regulation of soil phosphorus availability in alpine meadows: Insights from phosphate-mobilising bacteria. *Appl. Soil Ecol.*, 204, 105730. <https://doi.org/10.1016/j.apsoil.2024.105730>
- Ramayah, T., Cheah, J.-H., Chuah, F., et al. (2016). Partial Least Squares Structural Equation Modeling. In *Handbook of Market Research* (Issue 1). Pearson Malaysia Sdn Bhd.
- Renger, M., Wessolek, G., Schwärzel, K., et al. (2002). Aspects of peat conservation and water management. *J. Plant Nutr. Soil Sci.*, 165(4), 487–493. [https://doi.org/10.1002/1522-2624\(200208\)165:4<487::aid-jpln487>3.0.co;2-c](https://doi.org/10.1002/1522-2624(200208)165:4<487::aid-jpln487>3.0.co;2-c)
- Richter, N. F., Schubring, S., Hauff, S., et al. (2020). When predictors of outcomes are necessary: guidelines for the combined use of PLS-SEM and NCA. *Ind. Manag. Data Syst.*, 120(12), 2243–2267. <https://doi.org/10.1108/imds-11-2019-0638>
- Smith, M. R., Rao, I. M., & Merchant, A. (2018). Source-sink relationships in crop plants and their influence on yield development and nutritional quality. *Front. in Plant Sci*, 871, 1–10. <https://doi.org/10.3389/fpls.2018.01889>
- Sutejo, Y., Saggaff, A., Rahayu, W., et al. (2017). Physical and chemical characteristics of fibrous peat. *AIP Conference Proceedings*, 1903(June). <https://doi.org/10.1063/1.5011609>
- Szajdak, L. W., Jezierski, A., Wegner, K., et al. (2020). Influence of drainage on peat organic matter: Implications for development, stability, and transformation. *Molecules*, 25(11). <https://doi.org/10.3390/molecules25112587>
- Taiz, L., Zeiger, E., Møller, I., et al. (2015). *Plant Physiology and Development* (6th ed.). Sinauer Associates.
- Teh, C. B. S., Cheah, S. S., Kulaveerasingam, H. (2024). Development and validation of an oil palm model for a wide range of planting densities and soil textures in Malaysian growing conditions. *Heliyon*, 10(14), e32561. <https://doi.org/10.1016/j.heliyon.2024.e32561>
- Troville, J., Moisesescu, O. I., Radomir, L. (2025). Using necessary condition analysis to complement multigroup analysis in partial least squares structural equation modeling. *J. Retail. Consum. Serv.*, 82, 104018. <https://doi.org/10.1016/j.jretconser.2024.104018>
- van der Sloot, M., Kleijn, D., De Deyn, G. B., et al. (2022). Carbon to nitrogen ratio and quantity of organic amendment interactively affect crop growth and soil mineral N retention. *Crop Environ.*, 7(3), 161–167. <https://doi.org/10.1016/j.crope.2022.08.001>
- Veloo, R., Ranst, E. Van, & Selliah, P. (2015). NJAS - Wageningen Journal of Life Sciences Peat Characteristics and its Impact on Oil Palm Yield. *NJAS - Wageningen Journal of Life Sciences*, 72–73, 33–40. <https://doi.org/10.1016/j.njas.2014.11.001>
- Widiarso, B., Minardi, S., Komariah, Chandra, T. O., et al. (2020). Predicting peatland groundwater table and soil moisture dynamics affected by drainage level. *Sains Tanah*, 17(1), 42–49. <https://doi.org/10.20961/stjsa.v17i1.38459>
- Wu, W., Du, X., Qin, Z., et al. (2024). Integrated Rice-Snail-Crayfish Farming System Shapes Soil Microbial Community by Enhancing pH and Microbial Biomass in South Subtropical China. *Agriculture (Switzerland)*, 14(12), 2133; <https://doi.org/10.3390/agriculture14122133>
- Zayed, O., Hewedy, O. A., Abdelmoteleb, A., et al. (2023). Nitrogen journey in plants: from uptake to metabolism, stress response, and microbe interaction. *Biomolecules*, 13(10), 1443; <https://doi.org/10.3390/biom13101443>