

# Integrating nutrient distribution and use efficiency to develop NUE-based fertilization strategies for *Acacia* hybrid on tropical peat soils

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**Abstract.** *Triatmojo LP, Pulunggono HB, Hidayat Y, Pessotti PRR, Simbolon DR, Santos VDM, Siregar STH, Sandoval AJD, Hasibuan KA, Suparmanto A, Chakim L. 2026. Integrating nutrient distribution and use efficiency to develop NUE-based fertilization strategies for Acacia hybrid on tropical peat soils. Asian J For 10 (1): r100128. <https://doi.org/10.13057/asianjfor/r100128>. This study evaluated nutrient distribution and Nutrient Use Efficiency (NUE) of *Acacia* hybrid grown on tropical peat soils to support nutrient management for subsequent rotations. The assessment integrated stand characteristics, biomass nutrient partitioning, harvest residue return, and nutrient balance estimation. Results showed that although the merchantable stem accounted for the largest proportion of total biomass, more than half of both macro- and micronutrients were retained in nonmerchantable components, including bark, branches, leaves, and roots. This distribution indicates that nutrient capital is largely stored outside the harvested stem. Post-harvest estimates further demonstrated that residue retention returns a substantial proportion of nutrients to the site, confirming the significant role of harvest residues in internal nutrient cycling on peat soils. NUE analysis revealed contrasting nutrient utilization patterns among elements. Phosphorus showed high efficiency in supporting stem biomass production, whereas nitrogen exhibited lower efficiency, consistent with the species' nitrogen-fixing capacity and high nitrogen accumulation in biomass. Among base cations, comparatively lower balance margins were identified for potassium, sulfur, calcium, and magnesium when harvest residue inputs, NUE, and soil nutrient status were integrated. The nutrient balance assessment projected that most nutrients remain sufficient to sustain the next rotation under residue retention, while potassium, sulfur, calcium, and magnesium may require closer management attention. These findings demonstrate that residue conservation is essential for maintaining nutrient supply in tropical peat plantations and that fertilization strategies should prioritize nutrients with lower projected balance margins rather than applying uniform nutrient inputs.*

**Keywords:** *Acacia* hybrid, biomass, NUE, peatland, phosphorus

**Abbreviations:** DBH: Diameter at Breast Height, MAI: Mean Annual Increment, NUE: Nutrient Use Efficiency, PPE: Personal Protective Equipment

## INTRODUCTION

*Acacia* hybrid (*A. mangium* × *A. auriculiformis*) has become one of the most important species in tropical plantation forestry due to its rapid growth, nitrogen-fixing capability, and adaptability to marginal and nutrient-deficient soils (Koutika and Richardson 2019; Le et al. 2021; Sunarti and Nirsatmanto 2021). The hybrid combines the fast growth and superior stem form of *A. mangium* with the higher tolerance of *A. auriculiformis* to pests, diseases, and environmental stress (Sunarti and Nirsatmanto 2020, 2021). These characteristics allow *Acacia* hybrid to maintain high productivity across a wide range of tropical environments, including degraded lands and low-fertility soils. Consequently, the species has been widely adopted

for industrial plantation development, particularly for pulpwood production and sustainable land-use programs in Indonesia, Vietnam, and other tropical regions (Le and Ha 2017; Sunarti and Nirsatmanto 2020, 2021; Wongprom et al. 2025).

Despite its strong growth performance, sustaining long-term productivity of *Acacia* hybrid plantations remains challenging, especially on tropical peat soils. Peatlands are wetland ecosystems formed through the accumulation of partially decomposed organic matter under waterlogged and anaerobic conditions, where organic matter production exceeds decomposition rates (Page dan Baird 2016). In tropical regions, peatlands represent one of the world's largest terrestrial carbon reservoirs and play an important role in global climate regulation (Leng et al. 2019; Ribeiro

et al. 2021). However, tropical peat soils are generally characterized by low nutrient availability and poor nutrient retention capacity. Essential macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) are often present in limited available forms because nutrients are largely stored within undecomposed organic matter (Sumawinata et al. 2019). As a result, nutrient limitation becomes one of the main constraints affecting plantation productivity on peatlands (Pulunggono et al. 2022). Under these conditions, effective nutrient management is essential to sustain stand growth and long-term plantation productivity (Hardiyanto et al. 2024).

The challenges associated with peatland plantation management are further intensified by the inherent physical and biochemical properties of peat soils. Tropical peatlands commonly exhibit high acidity, slow nutrient mineralization, low bulk density, and substantial nutrient losses through leaching under humid tropical climates (Wang et al. 2015; Huong et al. 2020). Although *Acacia* species are relatively tolerant of low-fertility environments, repeated biomass harvesting may continuously remove large amounts of nutrients from the ecosystem. Over successive rotations, this nutrient export can accelerate soil nutrient depletion, reduce site fertility, and potentially lower plantation productivity if nutrient inputs are not properly managed (Laurén et al. 2021; Nieminen et al. 2022). Therefore, nutrient management strategies are needed not only to maintain biomass production but also to preserve peat soil function and long-term ecosystem sustainability.

Nutrient cycling within plantation ecosystems plays an important role in determining long-term productivity because nutrients are unevenly distributed among tree components such as stem wood, bark, branches, and leaves. Nutrient-rich tissues, particularly leaves and bark, generally contain higher nutrient concentrations than stem wood, even though stem wood contributes the largest proportion of total biomass (Rodríguez-Soalleiro et al. 2018; Rosell et al. 2023). Understanding nutrient distribution patterns is therefore important for estimating nutrient removal during harvesting and evaluating the contribution of harvest residues to nutrient recycling. Retention of nutrient-rich residues after harvesting may help reduce nutrient losses and improve nutrient availability for subsequent rotations. In addition, Nutrient Use Efficiency (NUE), defined as the amount of biomass produced per unit nutrient accumulated, provides important insight into how efficiently trees utilize limited nutrient resources under peatland conditions.

Although the growth performance of *Acacia* hybrid has been widely documented, quantitative integration of biomass nutrient distribution, Nutrient Use Efficiency (NUE), and rotation-based nutrient balance in tropical peat systems remains limited. In particular, insufficient attention has been given to how nutrient partitioning and harvest residue retention influence long-term nutrient sustainability on peat soils. Therefore, this study aims to (i) quantify nutrient distribution and NUE across tree components of *Acacia* hybrid planted on tropical peat soils, and (ii) integrate these findings into a nutrient balance approach to

support fertilization strategies for sustainable peatland plantation management.

## MATERIALS AND METHODS

### Study location

This study was carried out in Pelalawan District, Riau Province, Indonesia, about 171 km from Pekanbaru (Riau Province capital city). The study was conducted during April-October 2025. The study site has tropical humid climate characteristics, with an average annual rainfall of 2740.77 mm without any dry months (<100 mm/month) throughout the year, with average temperature of 23.48-32.67°C. Relative humidity remains stable across the year, with an average of 81.07%.

### Materials and tools

The tools used in this study consisted of equipment for collecting both biomass and soil samples. Biomass sampling was carried out using a chainsaw, hanging scale, rope, and standard Personal Protective Equipment (PPE) to ensure safety during fieldwork. Soil sampling was conducted using a Royal Eijelkamp peat auger with a 1000 cm<sup>3</sup> specification, accompanied by sample bags of 2 kg and 5 kg capacity, aluminum foil, plastic wrappers, cutting tools, cleaning tools, stationery, and a coolbox to properly store and preserve the soil samples.

The materials employed included a set of chemical reagents required for analyzing the chemical properties of both soil and plant samples in the laboratory (Table 1). These reagents supported the assessment of nutrient status and other relevant soil and plant characteristics, providing essential data for subsequent analysis.

### Plot establishment and sampling

The study was conducted in a 54-month-old *Acacia* hybrid plantation established at an initial spacing of 3×2 m (1,667 trees ha<sup>-1</sup>). At planting, the plants received a basal fertilizer application, followed by standard silviculture operational maintenance practices (weed and pest controls) during the first two years of stand establishment.

Within each plot, all trees-both living and dead-were measured for Diameter at Breast Height (DBH) and total height. Based on the stand inventory, five trees were selected across the plots for destructive sampling using two main criteria: (i) the trees were healthy, with no visible signs of disease, deformities, or pest infestation; and (ii) their growth performance was close to or slightly above the stand mean. This selection strategy was applied to ensure that the nutrient data obtained were representative of the overall stand conditions and aligned with the objectives of the study.

The selected living trees were felled using a chainsaw and separated into five components: stem, bark, branches, leaves, and roots. Each component was cleaned of adhering soil and debris and weighed fresh in the field using calibrated hanging digital scales. Root biomass was obtained through manual excavation of the entire root system within an estimated radius of 5 m and to a depth of

approximately 1 m, corresponding to the maximum rooting depth observed in root profile studies. Only main roots (coarse, medium, and small roots) were included in the analysis, while fine roots (<1 mm diameter) were excluded.

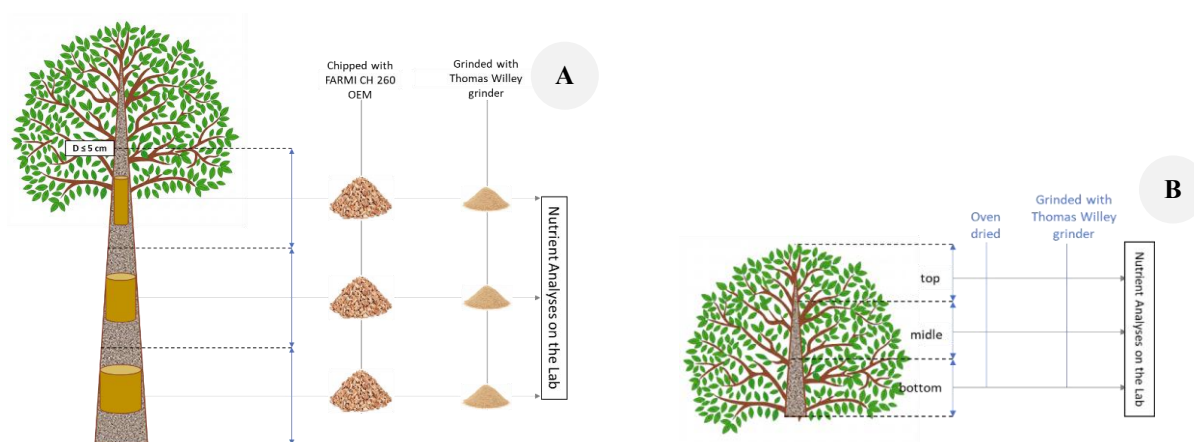
For stem and bark sampling, the entire tree length was sectioned at 1-m intervals, with representative samples taken from the bottom, middle, and top portions of the stem. Multi-stemmed (forked) trees were also classified as stem components. Leaves and branches were sampled from the lower, middle, and upper canopy positions, including primary, secondary, and tertiary branches (twig also

categorized as tertiary branches). For roots, all collected root materials from each tree were combined.

Leaf subsamples (200-500 g) were collected using paper envelopes (approximately 40 envelopes per sample). Stem, bark, branch, and root samples were chipped using a FARMI CH 260 OEM wood chipper then collected at 200-500 g each. All subsamples were oven-dried in a Memmer research oven and subsequently ground using a Thomas Wiley Mill (Model 4) prior to laboratory analysis (Figure 1).

**Table 1.** Details of materials and tools used for soil and plant nutrient analysis

Parameter	Sample type	Analytical method	Main reagents / Chemicals	Equipment / Tools
pH	Soil	Potentiometric (1:2.5 soil:water or soil:KCl)	Distilled water / 1N KCl	pH meter, beaker, stirrer
C-Organic	Soil	Walkley and Black (wet oxidation)	K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> , H <sub>2</sub> SO <sub>4</sub> , FeSO <sub>4</sub> , indicator (phenanthroline or ferroin)	Burette, pipette, hot plate, Erlenmeyer flask
N (Total)	Soil & Plant	Kjeldahl digestion-distillation	H <sub>2</sub> SO <sub>4</sub> , catalyst mix (K <sub>2</sub> SO <sub>4</sub> + CuSO <sub>4</sub> ), NaOH, boric acid, HCl	Digestion block, distillation unit, titration setup
P (Available / Total)	Soil (Bray I / Olsen), Plant (acid extract)	Spectrophotometry (blue molybdenum method)	NH <sub>4</sub> F + HCl (Bray I) / NaHCO <sub>3</sub> (Olsen), ammonium molybdate, ascorbic acid	Spectrophotometer, pipette, volumetric flask
K	Soil & Plant	Flame Photometry / AAS	NH <sub>4</sub> OAc (1N, pH 7) extractant	Flame photometer / Atomic Absorption Spectrophotometer (AAS)
S	Soil & Plant	Turbidimetry (BaSO <sub>4</sub> method)	Ca(H <sub>2</sub> PO <sub>4</sub> ) <sub>2</sub> or BaCl <sub>2</sub> solution	Spectrophotometer, shaker
Ca, Mg, Na	Soil & Plant	ICP-OES (NH <sub>4</sub> OAc extract)	NH <sub>4</sub> OAc (1N, pH 7)	ICP-OES, centrifuge
KTK (Cation Exchange Capacity)	Soil	Ammonium acetate (NH <sub>4</sub> OAc) saturation method	NH <sub>4</sub> OAc, ethanol, NaCl	Shaker, vacuum pump, measuring cylinder
Al, Fe, Mn, Zn, Cu, B	Soil & Plant	ICP-OES after acid digestion (HNO <sub>3</sub> -HClO <sub>4</sub> / H <sub>2</sub> SO <sub>4</sub> )	HNO <sub>3</sub> , HClO <sub>4</sub> , H <sub>2</sub> SO <sub>4</sub>	Digestion block, ICP-OES
Dry Weight	Plant	Oven-drying (constant weight)	-	Drying oven (70°C), analytical balance, desiccator



**Figure 1.** Illustration of A. Wood, bark, and B. Leaf sampling procedures in the field and subsequent sample processing from destructive sampling to laboratory analysis

## Data analysis

### Stand characteristics

Stand characteristics were explained based on individual trees diameter, height, dry weight, wood density, and also the Mean Annual Increment (MAI) at  $\text{ton ha}^{-1} \text{ year}^{-1}$ . Tree dry biomass were calculated by :

$$DW = FW \times (1 - {}_gWC)$$

Where:

DW: Biomass dry weight (kg)

FW: Fresh Weight (kg)

${}_gWC$ : Gravimetric water content (%)

Mean Annual Increment (MAI) at  $\text{ton ha}^{-1} \text{ year}^{-1}$  are predicted increment that calculated based on the merchantable stem weight (harvested with  $\leq 5\text{cm}$  diameter), at 1667 trees  $\text{ha}^{-1}$  initial stocking.

$$MAI = \frac{Ws \times 1667}{t}$$

Where:

MAI: Mean Annual Increment ( $\text{ton ha}^{-1} \text{ year}^{-1}$ )

Ws: Merchantable stem dry or fresh weight (ton)

1667: Numbers of initial stocking  $\text{ha}^{-1}$  if trees was planted with 2 x 3 m initial spacing

t: Time at harvested (year)

### Biomass nutrient and deposits potential

Biomass nutrient refers to the total amount of nutrients contained within the entire plant, calculated as the sum of nutrient contents in the stem, bark, branches, leaves, and roots. Nutrient deposit represents the portion of these nutrients that remains in the field as harvest residues, which serve as a source of nutrient return for the subsequent rotation.

Biomass nutrient for each tree component is estimated using a multiplicative model between biomass and nutrient concentration:

$$BN_i = DW_i \times NC_i$$

Where:

$BN_i$ : Biomass nutrient of component  $i$  (kg)

$DW_i$ : Dry weight of component  $i$  (kg)

$NC_i$ : Nutrient concentration of component  $i$  (%)

Total biomass nutrient for the whole tree is obtained by:

$$BN_{total} = \sum_{i=1}^n BN_i$$

Nutrient deposit is calculated as the difference between total biomass nutrient and the nutrient removed in the harvested stemwood:

$$ND = BN_{total} - BN_{stem}$$

Where:

ND : Nutrient deposit (kg)

$BN_{stem}$ : Biomass nutrient contained in the merchantable stemwood (kg)

### Nutrient Use Efficiency (NUE)

Nutrient Use Efficiency (NUE) was presented as amount of biomass/nutrient (Albuquerque et al. 2018; Guimarães et al. 2019; de Oliveira et al. 2025), describe how nutrients are absorbed and converted into plant biomass by specific component (each for stem, bark, branch, leaves, and roots). NUE was calculated using the following approach:

$$NUE_i = \frac{DW_i}{Ni}$$

Where:

$NUE_i$ : Nutrient Use Efficiency of Component  $i$  (biomass/nutrient)

$DW_i$ : Dry weight of component  $i$  (kg)

$Ni$ : Nutrient content in component  $i$  (kg)

### Nutrient ballancing

After determining the nutrient deposit and Nutrient Use Efficiency (NUE), nutrient adjustment was calculated using the nutrient balance concept (de Vries et al. 2021). This approach generates additional nutrient recommendations based on nutrient allocation characteristics, while also accounting for the nutrients returned to the field through biomass residues and the nutrients available in the soil for plant uptake.

The amount of nutrients potentially available from biomass was estimated using a predicted biomass loss equation that represent the proportion of total nutrients released through decomposition and thus available for plant uptake (Van Bich et al. 2018). Predicted biomass remaining after decomposition at  $t$  days can be calculated using this equation below :

$$\text{Bark: } 99.016e^{-0.0006t}; R^2=0.98; p<0.0001; n=7$$

$$\text{Branch: } 105.75e^{-0.001t}; R^2=0.97; p<0.0001; n=7$$

$$\text{Leaf: } 89.14e^{-0.004t}; R^2=0.98; p<0.0001; n=10$$

For this adjustment, a decomposition period of approximately one year was counted ( $t=365$ ). This one-year timeframe was selected because several Acacia species are capable of responding to additional nutrient inputs, including fertilizer, within its first year of growth (Mendham et al. 2017). Accordingly, the predicted proportion of biomass loss from harvest residues after one year of decomposition was estimated to be 0.792 for leaves, 0.266 for branches, and 0.205 for bark. Roots were not included as a source of nutrient availability within the one-year period because several studies indicate that nearly 90% of tree root biomass remains intact in tropical peat soils over this timeframe (Dargie et al. 2024), contributing minimally to short-term nutrient release.

$$\text{Nutrient Needs (kg ha}^{-1}\text{)} = \frac{SHT \times 1000}{NUEt/S} - (Ns + (Nd \times naC))$$

Where:

SHT: Stem harvest target ( $\text{ton ha}^{-1}$ )

NUEt: Total tree Nutrient Use Efficiency

S: Stem proportion of total biomass (%)

Ns: Nutrient available from soil by effective root zone (0-50 cm) ( $\text{kg ha}^{-1}$ )

N<sub>*i*</sub>: Nutrient potential from biomass deposit by component *i* (kg ha<sup>-1</sup>)

BL<sub>c</sub>: Predicted biomass loss coefficient at 4.5 year

## RESULTS AND DISCUSSION

### Growth characteristics of *Acacia hybrid*

The *Acacia* hybrid trees evaluated in this study (Table 2), having uniform stem dimensions and biomass attributes. The mean DBH reached 20.15 cm and height 23.80 m, with Coefficient of Variance (CV 5% and 6%). Wood density averaged 0.57 g cm<sup>-3</sup>, a value typical of fast-growing species that balances rapid cell expansion with sufficient structural strength (Duc et al. 2020; Malek et al. 2025).

Biomass traits also demonstrated strong productivity. The average total fresh biomass reached 516.76 kg per tree, corresponding to 251.46 kg of dry mass, while the merchantable stem contributed a substantial portion of this biomass (309.42 kg fresh and 152.18 kg dry). The relatively small standard deviations and tight confidence intervals imply stable biomass production across sampled trees. Mean Annual Increment (MAI) was notably high at 114.62 ton ha<sup>-1</sup> year<sup>-1</sup> for fresh biomass (56.37 ton ha<sup>-1</sup> year<sup>-1</sup> dry).

### Biomass distribution and nutrient allocation pattern

The biomass distribution of *Acacia* hybrid showed a clear dominance of the stem component, contributing 152.18 kg of dry weight, or 61% of the total tree biomass portion (Table 3). Roots represented the second-largest biomass by portion at 40.88 kg (16%), followed by branches at 30.57 kg (12%), bark at 19.63 kg (8%), and leaves at 8.20 kg (3%). Overall, the average total dry biomass per tree reached 251.46 kg, indicating a biomass allocation pattern that is strongly concentrated in structural tissues.

Macronutrient concentrations varied substantially among tree components, with leaves exhibiting the highest levels of nitrogen, phosphorus, and potassium, respectively (Table 3). Bark also contained relatively high macronutrient levels, particularly nitrogen (1.46%) and calcium (1.31%). In contrast, the stem consistently showed the lowest nutrient concentrations across all elements, including 0.38% N, 0.04% P, and 0.12% K.

Micronutrient distribution (Table 4) also differed markedly among tree components, with leaves containing the highest concentrations of sodium (2862.94 ppm), iron (44.71 ppm), manganese (229.94 ppm), zinc (7.22 ppm), copper (3.78 ppm), and boron (38.92 ppm). Roots exhibited the highest aluminum concentration at 144.58 ppm, while bark and branches showed intermediate concentrations for most elements. The stem consistently recorded the lowest micronutrient levels, including 303.73 ppm Na, 40.80 ppm Al, and 23.38 ppm Mn.

Overall, the distribution of nutrients within tree components showed clear differences in both macronutrient and micronutrient accumulation. Stems contained the

largest portion of total nutrient mass, followed by roots and branches, while leaves-despite contributing only around 3% of total biomass-held comparatively higher concentrations of N, P, and selected micronutrients.

### Nutrient stocks

The nutrient stock of *Acacia* hybrid biomass per hectare (Table 5) shows that macronutrients were dominated by nitrogen (2.87 ton ha<sup>-1</sup>), calcium (1.56 ton ha<sup>-1</sup>), and potassium (0.83 ton ha<sup>-1</sup>). These three nutrients represent the major components of plant nutrition in woody species. Nitrogen was mainly concentrated in the leaves and bark, reflecting their high metabolic activity and photosynthetic demand, whereas calcium and potassium were largely stored in the stem and roots.

Micronutrient accumulation showed a similar pattern (Table 5), where Na and Al dominated the total pool (195.47 and 24.79 kg/ha, respectively), followed by Fe and Mn. As illustrated in Figure 2, the stem accounted for more than 50% of both macronutrient and micronutrient stocks, followed by the roots and branches. Although the leaf fraction represented only about 3% of the total biomass, it contained proportionally higher concentrations of N, P, and several micronutrients.

Figure 2 illustrates the proportional distribution of macronutrients and micronutrients among the five biomass components of *Acacia* hybrid-bark, branch, leaf, roots, and stem-expressed as percentage contribution to total nutrient stock per hectare. For macronutrients the stem consistently contributed the largest share across all elements, generally exceeding 50% of total stocks. Roots represented the second-largest portion, particularly for Ca and Mg, while branches contributed moderate proportions across nutrients. Leaves, despite forming a small fraction of total biomass, accounted for a visibly higher proportion of nitrogen and phosphorus relative to other macronutrients.

A similar pattern was observed for micronutrients, where the stem again dominated the total accumulation of Na, Al, Fe, Mn, Zn, Cu, and B. Roots contributed the next largest share, especially for Al and Fe, followed by branches. Leaves consistently showed smaller overall contributions but maintained relatively higher proportions for micronutrients with strong metabolic roles such as Mn and Zn. Bark displayed moderate contributions across most elements, particularly for Na and B.

Based on the distribution of macro and micronutrients across tree components, stem consistently contributing the largest share of total nutrient stocks, followed by the roots and branches, while the leaves, despite their small biomass portion, retain comparatively higher nutrient concentrations. These results provide a clear overview of how nutrients are stored within the stand at harvest age (54 month), and the subsequent section will present a detailed assessment of nutrient deposits that can be recovered through harvest residues, both with or without debarking scenarios.

**Table 2.** Stand and tree characteristics of *Acacia* hybrid planted on tropical peatland

	DBH (cm)	Height (m)	Total biomass (kg)		Merchantable stem (kg)		Wood density (g cm <sup>-3</sup> )	MAI (ton ha <sup>-1</sup> year <sup>-1</sup> )	
			Fresh	Dry	Fresh	Dry		Fresh	Dry
Avg.	20.15	23.80	516.76	251.46	309.42	152.18	0.57	114.62	56.37
SD	1.01	1.44	72.02	36.14	36.14	22.91	0.02	16.35	8.49
CV	5%	6%	14%	14%	14%	15%	3%	14%	15%
Upper CI	21.55	25.79	616.74	301.62	370.68	183.98	0.58	137.32	68.15
Lower CI	18.74	21.81	416.78	201.29	248.16	120.38	0.56	91.93	44.59

Note: DBH: Diameter at Breast Height (1.3 m), MAI: Mean Annual Increment (calculated from the current stem results at 1,667 trees ha<sup>-1</sup>, divided by 4.5 years (54 months), which is the tree age at harvest in this study, assuming a 100% survival rate)

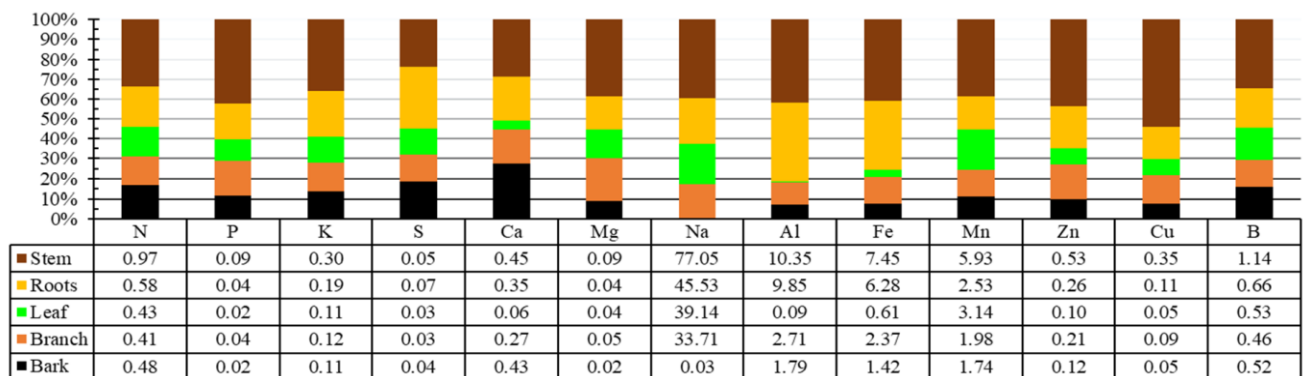
**Table 3.** Biomass distribution and its macronutrient content of *Acacia* hybrid planted on tropical peatland

Part	Dry weight (kg)	Portion	Nutrient content (%) / Tree					
			N	P	K	S	Ca	Mg
Bark	19.63	8%	1.46±0.40	0.08±0.02	0.35±0.08	0.12±0.04	1.31±0.47	0.07±0.03
Branch	30.57	12%	0.81±0.28	0.07±0.02	0.23±0.06	0.06±0.02	0.53±0.16	0.10±0.05
Leaf	8.20	3%	3.12±0.68	0.17±0.02	0.79±0.10	0.20±0.03	0.47±0.15	0.26±0.03
Roots	40.88	16%	0.86±0.22	0.06±0.01	0.28±0.10	0.10±0.03	0.51±0.17	0.06±0.02
Stem	152.18	61%	0.38±0.30	0.04±0.02	0.12±0.05	0.02±0.02	0.18±0.24	0.04±0.03
Total	251.46	100%						

**Table 4.** Biomass micronutrient content of *Acacia* hybrid planted on tropical peatland

Part	Micro nutrient content (ppm) / Tree						
	Na	Al	Fe	Mn	Zn	Cu	B
Bark	887.19±299.33	54.76±19.89	43.43±15.74	53.24±12.93	3.76±1.17	1.52±1.04	15.91±10.38
Branch	661.57±400.21	53.18±15.36	46.53±16.93	38.81±10.04	4.11±2.32	1.72±0.62	8.94±2.70
Leaf	2862.94±461.41	6.26±2.89	44.71±8.63	229.94±41.01	7.22±3.50	3.78±2.89	38.92±8.83
Roots	668.16±294.84	144.58±68.97	92.21±44.39	37.12±9.37	3.84±1.65	1.55±0.88	9.74±5.72
Stem	303.73±156.33	40.80±13.12	29.37±12.25	23.38±8.63	2.11±1.01	1.36±0.58	4.50±1.97

Note: The data for dry Weight (kg), and portion (%) are exactly the same as presented in Table 3

**Figure 2.** Distribution of biomass macro and micronutrients of *Acacia* hybrid planted on tropical peatland

### Nutrient deposit potential from harvest residues

Macronutrient deposits varied considerably among elements and between harvesting treatments scenario (Figure 3.A). Under debarking conditions, nitrogen showed the highest return (1.42 ton ha<sup>-1</sup> rotation<sup>-1</sup>), followed by magnesium (0.68 ton ha<sup>-1</sup>) and potassium (0.42 ton ha<sup>-1</sup>). Debarked harvesting resulted in higher nutrient deposits

across most macronutrients, with N, K, and Mg reaching 1.90, 0.53, and 1.11 ton ha<sup>-1</sup> rotation<sup>-1</sup>, respectively. Elements such as P, Ca, and Na contributed relatively smaller quantities, although they displayed the same pattern of higher nutrient return when bark was retained. Overall, debarking scenarios can provide greater macronutrient deposits than without debarking on harvesting.

**Table 5.** Biomass nutrient stocks per hectare of *Acacia* hybrid planted on tropical peatland

Total biomass macronutrient (ton ha <sup>-1</sup> )		Total biomass micronutrient (kg ha <sup>-1</sup> )	
N	2.87	Na	195.47
P	0.21	Al	24.79
K	0.83	Fe	18.14
S	0.21	Mn	15.32
Ca	1.56	Zn	1.23
Mg	0.24	Cu	0.64
		B	3.31

Note: Data were calculated with 1,667 initial stockings per hectare (2×3 m spacing)

Micronutrient deposits were dominated by Al, Fe, and Mn under both harvesting treatments (Figure 3.B). Without debarking, harvest residues contributed 12.65, 9.27, and 7.65 kg ha<sup>-1</sup> rotation<sup>-1</sup> for Al, Fe, and Mn, respectively, while debarked conditions increased these values to 14.44, 10.69, and 9.39 kg ha<sup>-1</sup>. Micronutrients present in smaller quantities, such as Zn (0.57-0.69 kg ha<sup>-1</sup>), Cu (0.25-0.29 kg ha<sup>-1</sup>), and Bo (1.65-2.17 kg ha<sup>-1</sup>). These results indicate that with debarking, harvest residues can contribute larger micronutrient pools than without debarking for all nutrient.

Overall, the results show that harvest residues serve as a substantial nutrient deposit, with debarking harvesting scenario consistently yielding higher macronutrient and micronutrient returns than without debarking. These quantified deposits provide a direct estimate of nutrient recycling potential per rotation and form the foundation for subsequent evaluation of nutrient use efficiency in *Acacia* hybrid plantations. Based on this approach, not all nutrients deposited in the field are available for plant uptake; instead, nutrient release is dominated by inputs from bark, branches, and leaves. Over one rotation, the proportion of nutrients released through decomposition of bark, branch, and leaf biomass is estimated at 64.95% (35.05% remaining), 48.39% (51.61% remaining), and 99.96% (0.04% remaining), respectively (Figure 4).

#### Nutrient Use Efficiency and the balancing of nutrients

The Nutrient Use Efficiency (NUE) of *Acacia* hybrid exhibited clear differentiation among tree components, reflecting contrasting physiological roles and nutrient allocation strategies (Figure 5). For macronutrients, the stem showed the highest NUE across all elements, indicating its dominant role in converting absorbed nutrients into long-term biomass. Branches and roots also demonstrated relatively high NUE for Ca, S, and Mg, suggesting that these structural tissues utilize nutrients more efficiently than foliage. In contrast, leaf consistently exhibited the lowest NUE due to their high nutrient concentrations but limited contribution to permanent biomass accumulation.

A similar pattern was observed for micronutrients. The stem again exhibited the highest NUE across all elements, particularly for Cu, Zn, and Bo which are essential for enzymatic activity, metabolic regulation, and structural development. Leaves maintained the lowest NUE for most micronutrients, reinforcing the general pattern of lower

nutrient efficiency in short-lived tissues (Schmidt et al. 2020). These results confirm that stemwood functions as the most nutrient-efficient component in *Acacia* hybrid, providing the greatest biomass produced per unit nutrient absorbed.

When expressed as NUE values for stem production, when ranked from the most to the least efficient (higher values indicate greater biomass produced per unit nutrient), the sequence becomes:

$$P > S > Mg > K > Ca > N$$

This ranking indicates that P and S were the most efficiently utilized macronutrients for stem biomass production in *Acacia* hybrid, whereas N showed the lowest efficiency despite its high absolute uptake (Figure 5).

For micronutrients, the NUE values in the stem ranked from the highest to the lowest efficiency, the order becomes: Cu > Zn > B > Mn > Fe > Al > Na

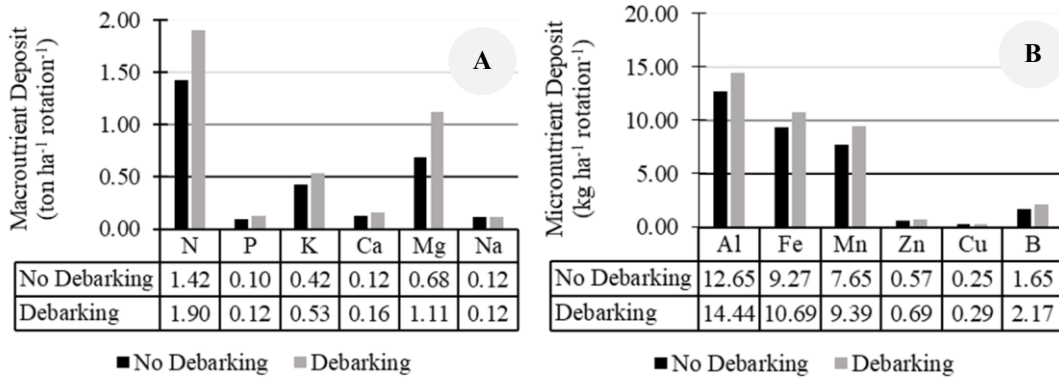
These results demonstrate that Cu and Zn were by far the most efficiently utilized micronutrients contributing to stem biomass accumulation, while Na showed the lowest NUE and minimal contribution to produce biomass (Figure 4). Similarly, the exceptionally high NUE values of Cu and Zn emphasize their strong catalytic roles in enzymatic and redox processes, where very small quantities support substantial biomass production (de Medeiros et al. 2021; Florentino et al. 2022).

The nutrient balance indicates that, after estimate the nutrient returns from harvest residues and soil nutrient, most macronutrients-particularly N and P are in surplus, resulting in negative additional requirements ( $\Delta N^-$ ). In contrast, K, S, Ca, and Mg are in deficit. These deficits indicate that K, S, Ca, and Mg remain insufficient even after integrating nutrient inputs from residues and soil availability.

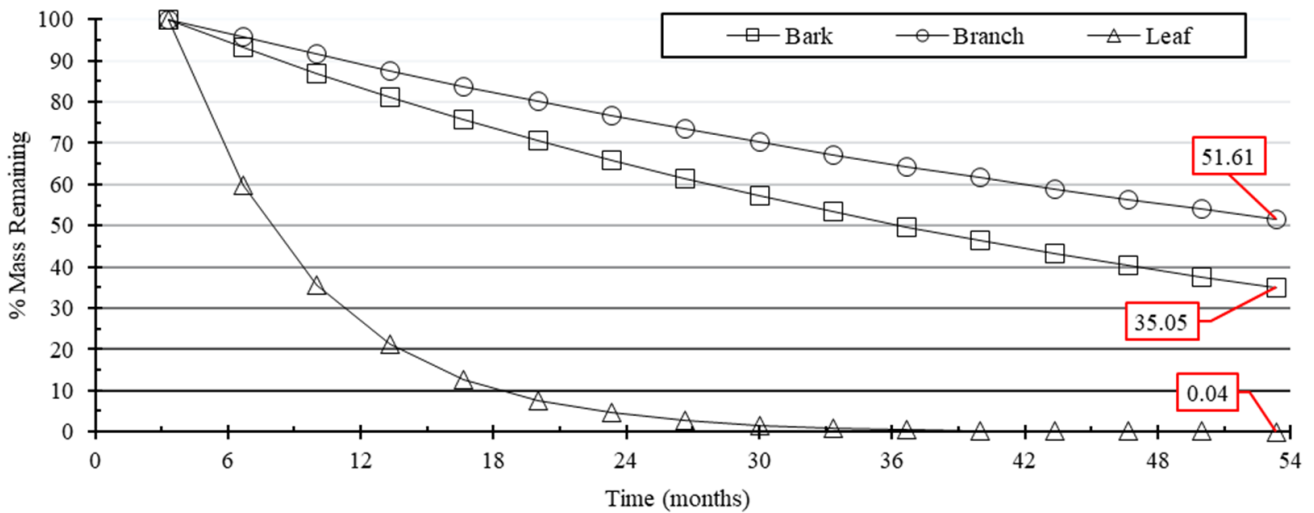
Micronutrient balances revealed substantial surpluses across all elements due to high contributions from soil reserves and harvest residues, resulting in negative additional requirements ( $\Delta N^-$ ) for every micronutrient. Therefore, no additional micronutrient additional required.

The nutrient balance presented in Table 6 shows that, based on the Nutrient Use Efficiency (NUE) values and the expected nutrient return from harvest residues, most macronutrients-particularly N and P-are in surplus when soil contributions are included, resulting in negative additional requirements ( $\Delta N^-$ ). In contrast, three macronutrients-K, Ca, and Mg-show positive additional values, indicating that these elements remain insufficient after accounting for both biomass-derived returns and soil availability. Specifically, potassium requires an additional 0.59 ton ha<sup>-1</sup>, calcium 1.05 ton ha<sup>-1</sup>, and magnesium 0.16 ton ha<sup>-1</sup> to meet the nutrient demands associated with the productivity target. For micronutrients, substantial surpluses were observed across all elements due to high contributions from soil and harvest residues, resulting in  $\Delta N^-$  for every micronutrient.

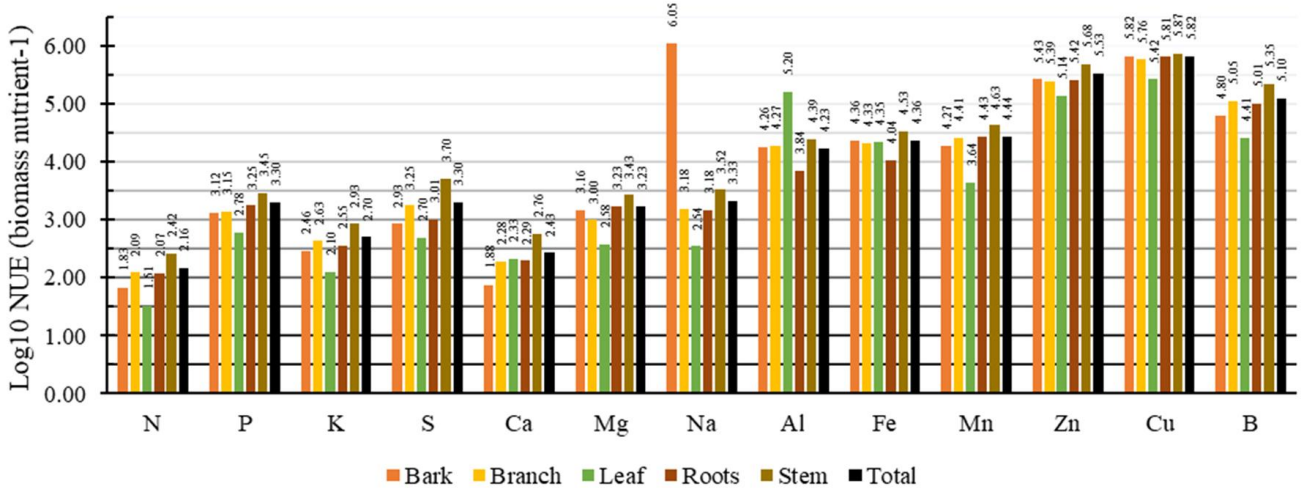
Overall, the table highlights that only K, Ca, and Mg require supplemental inputs to meet the nutrient demands derived from NUE-based estimates. Nevertheless, this recommendation still need to be tested through field trials to see the plant response to nutrient management.



**Figure 3.** Nutrient deposit potential in harvest residues of *Acacia* hybrid planted on tropical peatlands. A. Macronutrients and B. Micronutrients under unbarked and barked conditions



**Figure 4.** Predicted remaining mass from the onset of decomposition at planting until harvest age (4.5 years)



**Figure 5.** Nutrient Use Efficiency (NUE) of *Acacia* hybrid by tree component for macronutrients and micronutrients expressed with Log<sub>10</sub> value

**Table 6.** Nutrient balance derived from NUE analysis and remaining biomass stocks at stand level

	Macro nutrient needs (ton ha <sup>-1</sup> )						Micro nutrient needs (kg ha <sup>-1</sup> )						
	N	P	K	S	Ca	Mg	Na	Al	Fe	Mn	Zn	Cu	B
Requirement based on NUE	2.87	0.21	0.83	0.21	1.56	0.24	0.20	0.02	0.02	0.02	0.00	0.00	0.00
From Harvest Residue	0.94	0.06	0.24	0.07	0.47	0.08	55.46	2.56	2.68	5.23	0.28	0.13	1.09
Available from the Soil	7.11	17.34	0.01	0.00	0.04	0.01	0.00	0.02	256.15	7.99	1.52	0.41	0.00
Additional (a-b-c) Recommended Action	-5.18	-17.18	0.59	0.15	1.05	0.16	-55.27	-2.56	-258.81	-13.20	-1.80	-0.53	-1.09
	ΔN <sup>-</sup>	ΔN <sup>-</sup>	ΔN <sup>+</sup>	ΔN <sup>+</sup>	ΔN <sup>+</sup>	ΔN <sup>+</sup>	ΔN <sup>-</sup>	ΔN <sup>-</sup>	ΔN <sup>-</sup>	ΔN <sup>-</sup>	ΔN <sup>-</sup>	ΔN <sup>-</sup>	ΔN <sup>-</sup>

Note: Nutrient from harvest residue was calculated based on nutrient deposit from bark, branches, and leaves, considering the decomposition rates shown on Figure 4; ΔN<sup>+</sup>: Additional nutrient required; ΔN<sup>-</sup>: Additional nutrient not required due to nutrient surplus; Soil nutrient availability was estimated using an average bulk density of 0.1 g cm<sup>-3</sup> and a cultivation layer depth of 25 cm, with potential anaerobic conditions arising from water table fluctuations. The average soil pH is 3.55

## Discussion

The present study demonstrates that the *Acacia* hybrid (*A. mangium* × *A. auriculiformis*) grown on tropical peat soils exhibits good growth performance, also potentially strong and uniform (Table 2). That potential are common advantage in clonal forestry where selected genotypes express consistent phenotypic performance across plantation stands (Kim et al. 2011; Oluwajuwon et al. 2022). Similar patterns have been reported for *Acacia* hybrid on mineral soils, where vegetative propagation contributes to synchronized tree development and reduced within-stand variability (Le et al. 2021; Sunarti and Nirsatmanto 2021; Wongprom et al. 2025). Compared with previously published growth rates for *Acacia* hybrid in Southeast Asia, the productivity values observed in this study fall within the upper range for short-rotation pulpwood plantations (Sunarti and Nirsatmanto 2021), reinforcing the species suitability for nutrient-poor peat environments.

Biomass distributions further highlight the ecophysiological strategy of *Acacia* hybrid species in peat environments. The dominance of stem biomass (61% of total dry mass) aligns with typical allocation patterns of fast-growing tropical hardwoods, which prioritize stem development to maximize merchantable volume and height growth (Wongprom et al. 2025). The relatively small biomass contribution from leaves (3%) but high nutrient concentrations reflect the concentration of metabolic and photosynthetic activity in this tissue, a trend widely recognized in nutrient distribution studies (Rodríguez-Soalleiro et al. 2018; Bretherick et al. 2025). Root biomass (16%) also aligns with the species adaptive strategy to peat soils, where shallow anchorage, fluctuating aeration, and nutrient scarcity encourage the development of lateral root systems near the oxygen-rich upper peat layer (Malhotra et al. 2020; Krause and Lemay 2022; Rezapour et al. 2022).

Nutrient accumulation patterns among tree components reveal the functional specialization of tissues. Leaves store high concentrations of N and P due to their role in photosynthesis (Duan 2023). Conversely, stems contain lower nutrient concentrations associated with lignified structural tissues (Inagawa et al. 2023). Elevated Ca and Mg concentrations in bark highlight its physiological

importance in cambial regulation and its relatively high cation-binding capacity (Rosell et al. 2023).

At the stand level, macronutrient stocks were dominated by N, Ca, and K, which aligns with nutrient budget assessments in other *Acacia* plantations on nutrient-poor substrates. As a legume, *Acacia* fixes atmospheric nitrogen, boosting N stocks in biomass and soil, which is especially important on N-poor substrates (Albaugh et al. 2017; Voigtlaender et al. 2019). Calcium (Ca) and Potassium (K) are essential for rapid growth, cell wall structure (Ca), and osmoregulation (K). Fast-growing trees like *Acacia* efficiently acquire and cycle these nutrients through biomass and litterfall (Sumawinata et al. 2019; Urairak et al. 2020; Oliveira et al. 2021).

The particularly high stocks of Na and Al in tree tissues likely reflect the chemical characteristics of peat soils, which are acidic, rich in organic acids, and subject to cation competition under fluctuating water tables (Kassim and Yaacob 2019; Santiago-Rosario et al. 2021). Accumulation of Al is commonly reported in tree species grown on acidic peat and mineral soils with low pH. This occurs because low pH increases Al<sup>3+</sup> solubility, making it more available for uptake. Some tree species tolerate this through root exclusion, secretion of organic acids, or internal detoxification, safely storing Al in roots or leaves while minimizing metabolic disruption (Rahman et al. 2018; Zhao and Shen 2018; Ofoe et al. 2023; Zhu and Shen 2024). The distribution of these nutrient stocks among roots, bark, and stems demonstrates the importance of belowground and sub-merchantable components in nutrient storage at harvest age.

Harvest residue estimation highlights the substantial nutrient recycling potential within the system. When bark, small branches, and leaves are retained on site, large quantities of N, K, Mg, Al, and Fe can be returned to the soil, contributing to nutrient replenishment in subsequent rotations (Van Bich et al. 2018; Mendham and White 2019). This pattern is well documented in *Acacia* plantations where nutrient-rich bark and foliage serve as critical nutrient return pathways. Conversely, removal of bark or fine woody residues reduces the nutrient deposit potential for the site (Figure 4). These findings underscore

the necessity of residue retention as a core practice in sustainable management of peat plantations.

Nutrient Use Efficiency (NUE) analysis reveals that stems show the highest efficiency across all macronutrients, consistent with the large biomass produced per unit nutrient invested. The ranking of macronutrient efficiency (P>S>Mg>K>Ca>N) corresponds with the physiological roles of these nutrients in growth processes (Manu et al. 2022; González-Melo et al. 2025). The high NUE of micronutrients such as Cu and Zn reflects the low quantities required to support enzymatic and metabolic processes relative to biomass accumulation (de Medeiros et al. 2021; Florentino et al. 2022)

The nutrient balance estimation indicates that, compared to other macro- and micronutrients, K, Ca, S, and Mg tend to be in deficit. Consequently, additional fertilization is recommended to supply these nutrients. Deficits in these four elements are commonly observed in tropical peat soils derived from woody materials, which inherently contain very low concentrations of K, Ca, and Mg (Kunarso et al. 2022). Moreover, these nutrients are highly susceptible to leaching under acidic soil conditions.

Nevertheless, this does not imply that other nutrients can be entirely neglected. For phosphorus (P), several studies have shown that small inputs are still required to maintain optimal plant productivity (Mendham et al. 2017; Hardiyanto et al. 2021; Hardiyanto et al. 2024). In contrast, nitrogen (N) fertilization is generally unnecessary, as *Acacia* species are capable of fixing atmospheric N through symbiotic associations with N-fixing bacteria in root nodules.

Although nutrient balance calculations indicate adequate micronutrient supply for *Acacia* hybrid grown on peatlands, field observations revealed leaf yellowing symptoms consistent with micronutrient deficiency. The rapid recovery following EDTA-chelated micronutrient application suggests that the constraint was not total nutrient stock, but nutrient bioavailability. Peat soils contain high concentrations of organic acids with strong complexation capacity. These compounds can bind micronutrients such as Fe, Cu, and B, forming stable complexes that limit plant uptake despite sufficient total concentrations (Curtinrich et al. 2025). This discrepancy indicates that micronutrient availability in peat systems is controlled primarily by chemical speciation and complexation dynamics rather than by total nutrient reserves alone.

Therefore, fertilization strategies in peatland plantations should not rely solely on nutrient balance estimates but must also consider micronutrient speciation and soil chemical interactions. Targeted micronutrient application may remain necessary even when calculated nutrient stocks appear sufficient. Based on this, nutrient management in tropical peat forestry should prioritize base-cation restoration. Clonal uniformity enhances the predictability of nutrient responses within stands, making nutrient adjustments more precise and effective. Integrating fertilization with residue retention is necessary to maintain the sustainability of the site productivity.

Despite the discussions and recommendations presented, several limitations of this study provide clear opportunities for future research. The number of sampled trees was relatively small, although the selected individuals were uniform and represented the best-performing trees within the stand. In estimating nutrient release, this study was unable to develop site-specific decomposition rate equations and therefore relied on decomposition parameters derived from previous studies. In addition, fertilizer recommendations based on the nutrient balance approach require empirical validation to assess whether plant responses align with the predicted outcomes. Given the highly dynamic nature of tropical peat soils, this study also placed limited emphasis on environmental factors beyond soil fertility, such as hydrological conditions and microclimate, which may also play important roles in regulating plant growth.

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