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Nutrient leaching analysis in cover crop management to enhance the nutrient cycling process in coconut plantations

M C Tenjaya [1], Suwardi[2,3], P Oktariani [2,3], B Sumawinata [2], N I Fawzi [4], O Randrikasari [3*]
[1] Land Resource Management Study Program, IPB University, Bogor 16680, Indonesia
[2] Department of Soil Science and Land Resources, IPB University, Bogor 16680, Indonesia
[3]Center for Mine Reclamation Studies, International Research Institute for Environment and Climate Change, IPB University, Bogor 16144, Indonesia
[4] Tay Juhana Foundation, Penjaringan, North Jakarta 14440, Indonesia
Email: octaviana_rand@apps.ipb.ac.id

Abstract. This study investigates the dynamics of nutrient cycling within closed-system peatland ecosystems, focusing on the role of nutrient leaching in enhancing biomass productivity. Conducted in a coconut plantation in Pulau Burung District, Indragiri Hilir Regency, Riau Province, the research quantitatively assesses the leaching of essential nutrients into a 10 cm layer of peat soil resulting from cover crop decomposition. These cover crops, integral to the plantation's organic coconut production strategy, are managed through periodic cutting (every four months) and natural decomposition on the field. To closely replicate field conditions, the study employed a lysimeter method to measure the nutrients leached into the leachate. Over an observation period of eight weeks, nutrient leaching was systematically measured to determine the availability of nutrients to plants. Key findings include significant leaching rates of potassium (K) at 90.9 kg/ha/year, calcium (Ca) at 9.4 kg/ha/year, and iron (Fe) at 1109.9 g/ha/year through the peat layer. In contrast, the leaching of magnesium (Mg), copper (Cu), zinc (Zn), and manganese (Mn) was negligible, suggesting low concentrations in the cover crops and potential chelation, which impedes their mobility. This research highlights the critical role of cover crop management in promoting nutrient cycling, which is essential for sustaining the productivity and environmental health of peatland agricultural systems. The findings advocate for the integration of such practices into peatland management strategies to improve overall ecosystem sustainability.

1. INTRODUCTION

The nutrient cycling process is essential for maintaining ecosystems like tropical rainforests, which can serve as models for sustainable agricultural management [1]. A closed nutrient cycle, a natural process, ensures optimal biomass production through photosynthesis without relying on external inputs like synthetic fertilizers [2]. This nutrient cycling process not only proves to be economically viable but also significantly enhances agricultural sustainability.

In a closed system, nutrient availability for plants is sustained through the decomposition of litter and cover crops, which release nutrients back into the soil. Implementing nutrient cycling in agricultural management is especially critical in peatlands due to their inherent nutrient deficiencies. Previous research on nutrient dynamics within peatland agriculture in Indonesia concentrated on the industrial plantation of Acacia crassicarpa, which thrives without the addition of external nutrients [3]. The decomposition of this plant’s litter enriches the soil with essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), and sulfur (S), made accessible to plants primarily through the extensive network of fine roots in the upper layer of decomposed litter.

A similar outcome is observed with Acacia mangium, where nutrient cycling through the decomposition of litter and harvest residues substantially enriches the soil, benefiting subsequent crop rotations [4]. Despite the successful application of a closed nutrient cycle in forests and industrial forest plantations, its use in peatland agriculture has not yet been widely adopted. There is potential to significantly boost food commodity production and enhance regional welfare through improved agricultural practices in these areas [5].

In Indragiri Hilir, Riau Province, peatlands predominate the landscape and underpin the regional economy through extensive coconut plantations. A prominent operator in this sector, the Sambu Group, employs cover crop management as a standard agronomic practice to enhance nutrient cycling and sustain high productivity levels in coconut plantations. On the other hand, the dynamics of nutrient leaching from the decomposed biomass of cover crops, which are manually harvested every four months and predominantly consist of the fern Nephrolepis sp., as well as from coconut litter, are not well understood. Additionally, these plantations maintain high productivity without the application of synthetic fertilizers, a requisite for organic certification, raising questions about the mechanisms through which coconut trees acquire necessary nutrients.

The research aims to quantitatively assess the leaching of essential nutrients into a 10 cm layer of peat soil resulting from the decomposition of the cover crops. The research will focus on quantifying the soil concentrations of key nutrients such as K, Ca, Mg, Fe, Cu, Zn, and Mn. By elucidating these nutrient dynamics, the research aims to provide insights into the nutrient supply mechanisms in organically managed peatland coconut plantations.

2. METHODS

2.1 Study area

The research was conducted at a coconut plantation managed by the Sambu Group, located in the Pulau Burung District of Indragiri Hilir, Riau Province (Figure 1). This plantation occupies a portion of the Sungai Kampar Sungai Gaung Peatland Hydrological Unit, encompassing an area of 22,650 hectares. The coconut plantation has been obtained organic certification since 2015, following decades of preparation through sustainable management practices, including an integrated water management system developed in 1986 and properly managed since then.

The peatland is classified as coastal ombrogenous peat, which has been forming over the past 6,000 years [7]. This type of peatland is primarily fed by rainfall rather than river water, making it highly sensitive to changes in precipitation patterns. The region experiences an average annual rainfall of 1,875 mm, characterized by a bimodal distribution with peaks in April and November. These periods represent optimal times for conducting studies on nutrient leaching due to increased rainfall intensities, which can influence the rates of nutrient displacement and absorption within the soil profile.

2.2 Data and analysis

To quantitatively assess nutrient leaching from decomposed cover crops within a coconut plantation, lysimeter method was employed, simulating natural field conditions. Each lysimeter was constructed using plywood, measuring 40 cm in length, 30 cm in width, and 10 cm in height, and featured a small drainage hole at the bottom covered with a net to facilitate leachate collection.

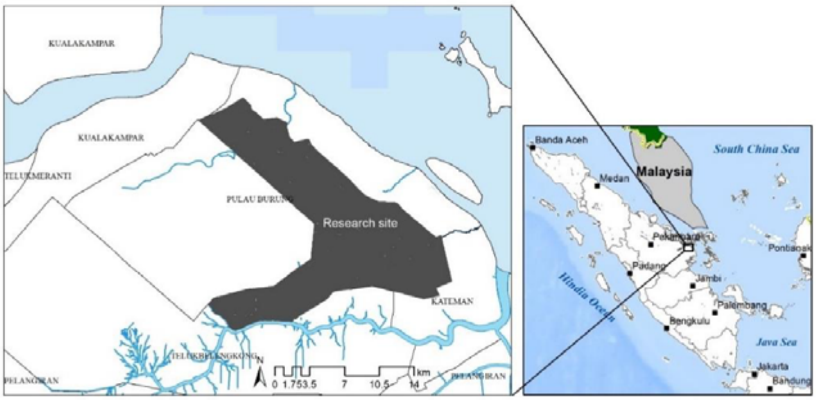


Figure 1. Map of the study area in a coconut plantation in Pulau Burung District.

These lysimeter containers were uniformly filled with peat soil from two planting blocks of a coconut plantation: 09.08 and K3.01 (Figure 2). At the same time, soil samples were also collected from the same planting blocks for chemical analysis. The experimental design included two variables: one set of lysimeters filled solely with peat soil from two planting blocks, serving as controls (labeled as: G), and two sets of peat soil with 300 grams of collected fresh cover crops to decompose naturally above the lysimeter (labeled as: GT) to replicate the natural decomposition process observed in the field (Figure 3). Hence, there were six lysimeter containers used. Therefore, six lysimeter containers were used in total. The cover crops, typically harvested manually every four months by the companies, were collected from a defined 1 x 1 m area at the age of 4 months. The collected cover crops species under the coconut canopy included Nephrolepis sp., Dicliptera chinensis, Sideria sp., and Stenochlaena palustris. These collected cover crops were placed atop the lysimeters, while additional samples were stored for biomass and nutrient analysis.

(a) (b) (c)

Figure 2. Step-by-step soil collection for lysimeter: (a) measure a 40 x 30 cm area, (b) cut the soil with a saw and dig around it, and (c) collect the soil in the same volume as the lysimeter and place it in the container.

Beneath each lysimeter, a 7-liter bucket was positioned to collect leachate, which was analyzed to assess the rate of nutrient leaching. This leachate was systematically collected following each rainfall event from September 17 to November 29, 2022, with precise records maintained for rainfall intensity and duration. Following each rainfall, leachate volumes were measured and stored for further analysis in the laboratory. Additionally, rainfall water was also collected and stored (labeled as: Kt) to serve as a benchmark for analysis of nutrient leaching from the lysimeters. The collected leachate was then classified into three categories: GT, G, and Kt, and presented on a weekly basis.

(a) (b)

Figure 3. (a) Lysimeter setup including decomposed cover crops placed above the peat soil, and (b) lysimeter containing only peat soil. Below each lysimeter setup, a bucket is positioned to collect leachate following each rainfall event.

Chemical analysis of the leachate was conducted at the Laboratory for Development of Land Physical Resources within the Department of Soil Science and Land Resources at the Faculty of Agriculture, IPB University. Essential nutrients such as Ca, Mg, Fe, Cu, Zn, and Mn were quantified using Atomic Absorption Spectrophotometry (AAS). Potassium (K) content was determined using flame photometry. Concurrently, the peat soil samples were subjected to the dry ashing method, a preparatory step for enhancing trace element detectability by converting organic and inorganic substances into ash. The resultant ash was dissolved, and the solution was further analyzed using both AAS and flame photometry to provide a detailed nutrient profile, facilitating a thorough understanding of the soil's chemical properties and the effects of cover crop decomposition on nutrient dynamics.

For the analysis of nutrient leaching from the lysimeters, the calculation is based on the following formula:

$$T = (GT - Kt) - (G - Kt) \quad \ldots(1)$$

Here, T represents the total leached nutrients adjusted for background levels, GT is the nutrient concentration in the leachate from the lysimeters containing peat soil and decomposed cover crops, G is the nutrient concentration in the leachate from the control lysimeters containing only peat soil, and Kt is the background nutrient concentration in the collected rainfall water.

To quantify the total nutrient leaching per unit area in milligrams per square meter (mg/m²), the following calculation is used:

$$\text{Nutrient concentration (ppm) x volume of collected water (L) x } \frac{1}{\text{area of lysimeter } (m^2)} \quad \ldots(2)$$

This calculation transforms the concentration of nutrients in parts per million (ppm) into a mass per unit area, considering the volume of water collected and the specific area of the lysimeter.

3. RESULTS AND DISCUSSION

3.1 Chemical characteristic of soil and cover crops

The chemical properties of the peat soil within the study area are presented in Table 1. Analyses indicate that the soil is highly acidic, with pH values ranging from 3.43 to 3.66. This acidity is indicative of typical peat soil conditions, which generally exhibit low nutrient content due to limited mineral input and high organic matter accumulation.

Table 1. Chemical analysis from peat soil

Block	Depth (cm)	pH H2O	K	Ca	Mg	Fe	Cu	Zn	Mn
			---------(me/100g)--------			----------(ppm)----------			
09.08	0-15	3,57	0,32	2,31	4,51	350,4	33,5	17,5	44,1
	5-15	3,66	0,44	2,85	5,23	309,6	23,0	12,0	41,0
K3.01	0-5	3,43	0,49	3,16	3,14	378,0	19,9	10,4	48,7
	5-15	3,56	0,64	4,34	2,64	363,2	25,0	13,1	18,9

In terms of nutrient cycling, the management of cover crops involves cutting them every four months. This practice yields approximately 0.79 kg/m² of dry biomass, equating to about 7.85 tons/ha/year. Annually, this results in approximately 23.55 tons/ha of decomposed plant material being reintegrated into the soil, thereby perpetuating a continuous cycle of organic matter replenishment. Concurrently, the regrowth of these cover crops contributes to carbon sequestration, potentially neutralizing an equivalent amount of carbon dioxide emissions.

Chemical analysis of the decomposed cover crops indicates significant nutrient release into the soil, including K at 1.95%, Ca at 0.33%, Mg at 0.90%, Fe at 97.4 ppm, Cu at 17.6 ppm, Zn at 36.0 ppm, and Mn at 41.3 ppm. The nutrient release from the cover crops is equivalent to the application of several forms of synthetic fertilizers: 1,229.7 kg of NPK 15-15-15 (for K_2O), 589.58 kg of Dolomite (for Ca and Mg), 3.822 kg of Iron Sulfate, 0.553 kg of Copper Sulfate, 0.785 kg of Zinc Sulfate, and 1.013 kg of Manganese Sulfate per 4-month cycle. When annualized, these quantities are multiplied by three. Additionally, the decomposition process results in a reduction of the initial dry weight of the cover crops by 68.16% [8], further enriching the peat soil with essential nutrients. This dynamic is critical for maintaining soil fertility and supporting the growth of coconut trees in this nutrient-deficient environment.

3.2 Volume of leachate and rainwater

During the 8-week observation period, 20 rainfall events were recorded. The volume of rainwater collected each week is showed in Table 2. This dataset is critical for analyzing the nutrient content within the collected rainwater. The data shows fluctuations in the volume of collected water over this period, highlighting variability in rainfall intensity and frequency. Significant differences are evident among the three types of lysimeters used in this study: those with peat soil and undergrowth (GT), those with only peat soil (G), and those capturing only rainfall (Kt). In total, approximately 20% of the rainwater is retained within the peat soil. In the GT and G, rainwater first percolates through layers of peat soil and/or decomposed cover crops. This condition allows for the assessment of nutrient leaching and retention differences between the lysimeter where soil and vegetation are present versus where only rainfall is measured.

Table 2. Volume of collected leachate and rainwater in eight-week measurement

Leachate code	Volume Total (L)								Total
	Week								
	1	2	3	4	5	6	7	8	
GT	8.32	0.34	19.10	10.14	9.31	5.53	10.25	6.69	69.67
G	8.36	0.18	19.09	10.18	9.21	4.80	9.76	6.62	68.19
Kt	4.56	0.40	31.03	11.72	11.53	6.02	11.01	7.90	84.19

3.3 Potassium (K) in leachate

The highest levels of K release were observed at 36.9 ppm in the first week and 25.7 ppm in the third week. The decomposed cover crops primarily released more potassium during the initial month of decomposition. By the end of the 8 weeks, the cover crops had fully decomposed, releasing all their potassium content into the soil. The K content in the leachate varied between the GT and G leachates. In the GT leachate, the decomposition of cover crops released nutrients that were then transported by water flow, enhancing the nutrient supply. The high K nutrient content in the cover crops, at 1.95%, significantly contributed to this elevated nutrient release. The nutrients released from the decomposed cover crops were leached by rainwater through the soil layers.

The total K leached from cover crop decomposition (T) over the 8 weeks amounted to 3029 mg/m², which is equivalent to approximately 90.9 kg/ha/year. Potassium leaching from cover crop decomposition was higher during the initial observation period, aided by heavy rainfall which facilitated nutrient leaching. Potassium leaching from cover crop decomposition through the soil layer was higher compared to other nutrients. This is attributed to potassium's high mobility in soil and plants [9]. Unlike some nutrients, potassium does not form stable compounds with other elements and is not bound within organic plant matter [10,11]. Rapid potassium release typically occurs during the early stages of decomposition, followed by minimal changes thereafter. Potassium is present in a highly soluble form, which leads to significant leaching during rainfall. Furthermore, the absence of potassium as a structural component in plant litter contributes to its easy leachability [12,13].

Table 3. Potassium (K) concentration in leachate

Leachate code	K (ppm)							
	Week							
	1	2	3	4	5	6	7	8
GT	50.3	13.8	48.8	30.7	40.5	9.3	16.1	3.8
G	13.3	8.6	23.1	13.7	22.0	4.2	7.3	1.9
Kt	1.3	3.2	2.1	0.6	1.9	0.4	1.0	0.3
T	36.9	5.2	25.7	17.0	18.5	5.1	8.8	1.9

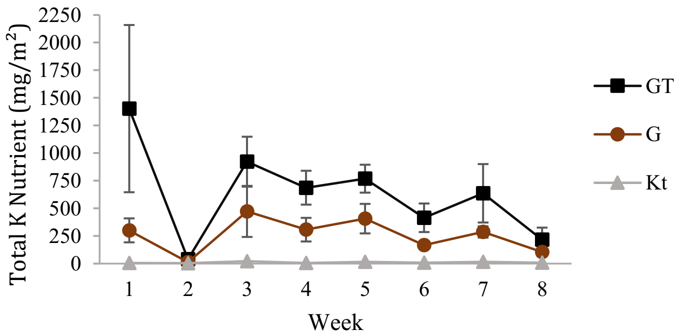


Figure 4. Potassium (K) nutrient released per unit area (mg/m²)

3.4 Calcium (Ca) in leachate

The highest release of calcium (Ca) from the decomposition of cover crops through soil leaching was measured at 7.1 ppm in week 3 (Table 4). The decomposition process primarily released more calcium during the initial five weeks of observation. Ranjbar & Jalali (2012) found that calcium release occurs rapidly in the first month, followed by a slower, more prolonged release [14], exhibiting a similar release pattern to potassium. The GT leachate displayed higher nutrient leaching from cover crop decomposition compared to the G leachate.

The total amount of calcium released by the decomposition of cover crops and subsequent leaching through the soil over the 8-week period was 313.5 mg/m², which equivalent to 9.4 kg/ha/year. The highest in calcium leaching in week 3 could be attributed to the substantial volume of leachate collected that week, totaling 31.03 liters. Higher rainfall during this period likely enhanced percolation flow through the root zone, which facilitated the release of salts from this zone, thereby promoting nutrient leaching [15].

Table 4. Calcium (Ca) concentration in leahcate

Leachate code	Ca (ppm)							
	Week							
	1	2	3	4	5	6	7	8
GT	8.3	3.0	12.8	5.4	7.3	1.4	2.2	0.7
G	5.6	2.7	5.6	3.9	4.6	1.0	1.8	0.5
Kt	0.4	2.9	0.8	0.5	0.8	0.0	0.0	0.0
T	2.7	0.3	7.1	1.5	2.8	0.3	0.4	0.2

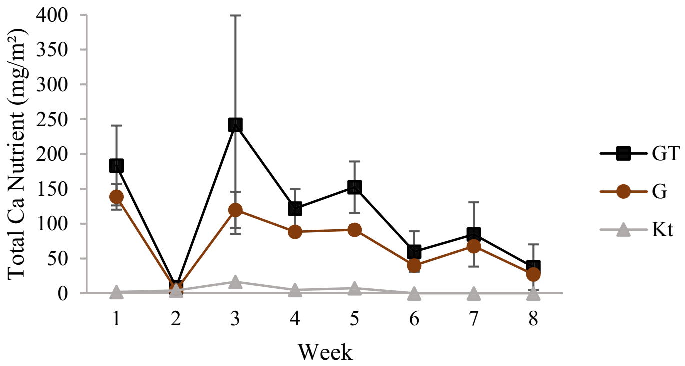


Figure 5. Calcium (Ca) nutrient released per unit area (mg/m²)

3.5 Magnesium (Mg) in leachate

Interestingly, magnesium (Mg) concentrations in the G leachate were consistently higher than those in the GT leachate. The peak leaching of this nutrient from the cover crops' decomposition was observed in week 3, with a concentration of 1.9 ppm. Although the differences in magnesium content between GT and G leachates were not substantial, the majority of the measurements showed higher magnesium concentrations in the G leachate than in the GT leachate (Figure 6). This observation suggests that the magnesium released by the decomposition of cover crops may remain partially unaccounted for in the collected water samples. Cover crops are known to contain relatively high levels of magnesium, but it is likely that the peat soil absorbs much of this magnesium, making it undetectable in the leachate. Further research is needed to investigate this phenomenon more thoroughly.

Table 5. Magnesium (Mg) concentration in leachate

Leachate code	Mg (ppm)							
	Week							
	1	2	3	4	5	6	7	8
GT	5.6	3.3	12.4	6.5	9.4	2.0	3.2	0.8
G	6.6	3.2	10.5	7.7	9.3	2.5	4.7	1.0
Kt	0.3	0.2	0.3	0.4	0.4	0.1	0.1	0.0
T	-1.0	0.1	1.9	-1.1	0.1	-0.5	-1.5	-0.2

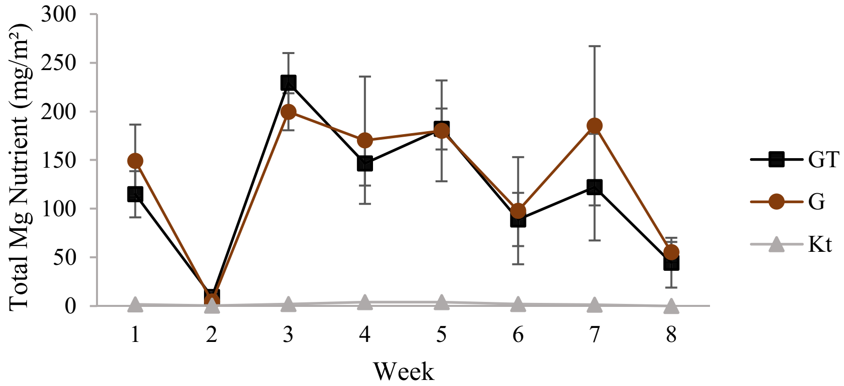


Figure 6. Magnesium (Mg) nutrient released per unit area (mg/m²)

3.6 Micronutrient leaching in leachate

The release of iron (Fe) is observed weekly, displaying variable trends across the study period. The most significant Fe release from cover crop decomposition occurred between weeks 3 and 5, with the highest leaching rate recorded in week 3. The maximal leaching of Fe through the soil (T) reached 0.60 ppm in week 5, whereas in week 1, Fe release was not detectable.

Figure 7a presents the total Fe content measured in the collected water over the eight-week period. GT leachate demonstrated higher Fe concentrations compared to G leachate, a result attributed to the nutrient influx from the decomposition of cover crops. Iron, due to its higher concentration in the decomposed material, exhibited more substantial leaching compared to other micronutrients. The cumulative Fe released by the decomposition of cover crops through the soil amounted to 37 mg/m² over 8 weeks, translating to 1109.9 g/ha/year. Some of the Fe released by the decomposition process is carried away with rainwater, while a portion may remain un-leached due to incomplete decomposition within the 8-week timeframe. Furthermore, iron may also be present in the soil matrix, thus only partially available for leaching. In peat soils, iron is often complexed with humic substances [16].

Copper (Cu) leaching from the decomposition of cover crops was not measurable in both GT and G leachates, likely due to the minimal Cu content in the cover crops and strong chelation by organic matter, which effectively binds copper within the soil matrix. Although Cu release from cover crops was not detectable in this study, another investigation reported Cu release at a rate of 39.7 mg/m² over 8 weeks, equivalent to 119.2 g/ha/year [17]. Nonetheless, this released Cu is presumed not to leach significantly due to the strong chelation properties of peat soil, making it undetectable in the collected water samples [18,19].

The concentration of zinc (Zn) leaching from the decomposition of cover crops reached a maximum of 0.03 ppm in week 5. Although the Zn content in GT leachate did not significantly differ from G leachate, it was observed to be higher in G leachate than in GT. This discrepancy likely arises from the intrinsically low Zn content in the cover crops. Additionally, the limited leaching of Zn can be attributed to the strong adsorptive properties of peat soil, which effectively immobilizes Zn. This behavior is characteristic of peat soils, where micronutrients such as Cu and Zn exhibit low availability due to complexation and strong adsorption, limiting the efficacy of fertilizer applications for growth enhancement [20,21].

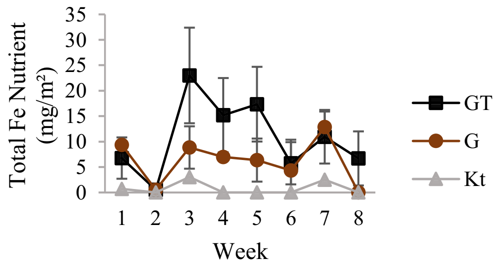
Table 6. Micronutrients concentration in leachate

Micronutrients	Leachate code	Concentration (ppm)							
		Week							
		1	2	3	4	5	6	7	8
Fe	GT	0.37	0.21	0.85	0.68	0.94	0.12	0.27	0.12
	G	0.44	0.20	0.42	0.37	0.34	0.10	0.24	0.00
	Kt	0.12	0.00	0.11	0.00	0.00	0.00	0.11	0.00
	T	-0.07	0.01	0.43	0.30	0.60	0.02	0.03	0.12
Cu	GT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Kt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	T	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	GT	0.06	0.03	0.17	0.00	0.03	0.00	0.00	0.00
	G	0.08	0.05	0.16	0.00	0.00	0.00	0.00	0.00
	Kt	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00
	T	-0.02	-0.02	0.01	0.00	0.03	0.00	0.00	0.00
Mn	GT	0.74	0.51	1.07	0.59	0.70	0.18	0.27	0.12
	G	0.65	0.32	1.09	0.64	0.80	0.18	0.36	0.07
	Kt	0.63	0.00	0.60	0.24	0.36	0.10	0.10	0.00
	T	0.09	0.19	-0.02	-0.05	-0.10	0.00	-0.09	0.05

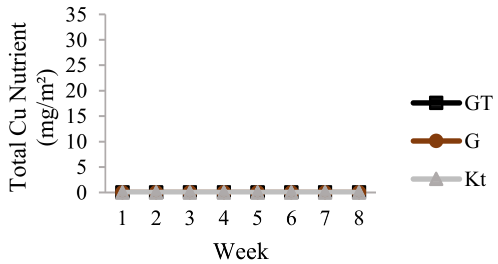
The leaching of manganese (Mn) displayed variable trends. Mn released from the decomposition of cover crops did not leach, presumably due to the strong binding affinity of peat soil, which retains Mn within the soil matrix [22].

Variations in nutrient leaching observed weekly can be linked to changes in rainfall volume and intensity, differences in the types and quantities of cover crops utilized, and the initial nutrient content of the cover crops. As a result, nutrient release from the decomposition of cover crops through the soil matrix remains low, particularly for nutrients that are strongly bound by organic constituents.

In summary, the leaching of micronutrients, including Fe, Cu, Zn, and Mn, from the decomposition of cover crops through the soil layer in peatland ecosystems is influenced by various factors such as rainfall patterns, undergrowth composition, and soil characteristics. While Fe leaching is significant, leaching of Cu and Zn was not detectable, likely due to their low presence in undergrowth and their strong affinity for organic constituents in peat soil. Mn leaching was also undetectable due to its strong chelation by peat soil [23]. These findings illustrate the complex interdependencies among vegetation, soil, and environmental factors that determine micronutrient leaching dynamics in peatland ecosystems, highlighting the need for further research to more effectively understand and manage nutrient dynamics in these environments.



(a)



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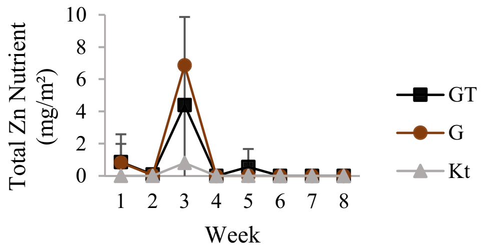

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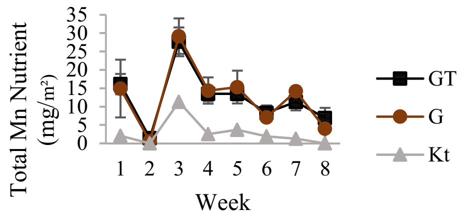

(d)

Figure 7. The release of micronutrients, including Fe (a), Cu (b), Zn (c), and Mn (d), per unit area (mg/m²) over an 8-week period

4. CONCLUSION

The decomposition of cover crops results in the gradual leaching of nutrients, which subsequently become available to crops. Specifically, potassium (K) leaches from the decomposition through a 10 cm layer of peat soil at a rate of 90.9 kg/ha/year, calcium (Ca) at 9.4 kg/ha/year, and iron (Fe) at 1109.9 g/ha/year. The negligible leaching of magnesium (Mg), copper (Cu), zinc (Zn), and manganese (Mn) suggests their low concentrations in the cover crops' nutrient profile and possible chelation, which reduces their mobility.

This research concludes that nutrient cycling occurs through the nutrients released from the decomposition of cover crops into the soil. This supports the observation that coconut productivity on peat soil remains optimal without the need for external synthetic fertilizer inputs. These findings are crucial for enhancing sustainable agricultural practices in peatland environments.

REFERENCES

[1] Subagiyo L, Herliani, Sudarman, and Haryanto Z 2019 *Literasi Hutan Tropis Lembab dan Lingkungannya* (Mulawarman : University Press)
[2] Jorgensen J R, Wells C G and Metz L J 1975 *J. Forestry* **73** 400–403
[3] Sumawinata B, Djajakirana G, Suwardi, and Darmawan 2019 *IOP Conference Series: Earth and Environmental Science* vol 393 (IOP Publishing) p 012029
[4] Van Bich N, Eyles A, Mendham D, Dong T L, Ratkowsky D, Evans K J, Hai V D, Thanh H V, Thinh N V, and Mohammed C 2018 *Forests* **9** 577
[5] Zamaya Y, Tampubolon D, and Misdawita M 2021 *J. Planol.* **18** 198–212
[6] Mupita J, Widiaty I and Abdullah A G 2018 How important is technological, pedagogical, content knowledge? A literature reviews *IOP Conference Series: Materials Science and Engineering* vol 434 (IOP Publishing) p 12285
[7] Furukawa H 1994 *Coastal wetlands of Indonesia: Environment, subsistence and exploitation* (Japan: Kyoto University Press)
[8] Wijaya P K S 2023 *Undergraduate thesis* (Bogor: IPB University)
[9] Oktariani P, Hadiwijaya D D, Sumawinata B and Djajakirana G 2023 *IOP Conference Series: Earth and Environmental Science* vol 1266 (IOP Publishing) p 012070
[10] Marschner H 1995 *Mineral Nutrition of Higher Plants* (Gulf Professional Publishing)
[11] Rosolem C A, Mallarino A P and Nogueira T A R 2021 *Considerations for Unharvested Plant Potassium Improving Potassium Recommendations for Agricultural* Crops ed T S Murrell, R L Mikkelsen, G Sulewski, R Norton and M L Thompson (*Cham: Springer International Publishing*) pp 147–62
[12] Werle R, Garcia R A, and Rosolem C A 2008 *Rev. Bras. Ciênc. Solo* **32** 297–305
[13] Jalali M and Jalali M 2022 *J. Soil Sci. Plant Nutr.* **22** 1290–1304
[14] Ranjbar F and Jalali M 2012 *Commun. in Soil Sci. Plant Anal.* **43** 645–59
[15] Hess L J T, Hinckley E-L S, Robertson G P, Hamilton S K, and Matson P A 2018 *Vadose Zone J.* **17** 180128

[16] Gerke J 2021 *J. Plant Nutr. Soil Sci.* **184** 329–338
[17] Hadiwijaya D D 2023 *Undergraduate thesis* (Bogor: IPB University)
[18] Naganuma K, Okazaki M, Yonebayashi K, Kyuma K, Vijarnsorn P and Bakar Z A 1993 *Soil Sci. Plant Nutr.* **39** 455–462
[19] McBride M B 2001 *J. Environ. Qual.* **30** 78–84
[20] Twardowska I and Kyziol J 2003 *Environ. Inter.* **28** 783–791
[21] Hafeez B, Khanif Y M and Saleem M 2013 *J. of Exp. Agric. Inter.* **3** 374–391
[22] Stepniewska Z, Sochaczewska A, Wolińska A, Anna S-N and Paszczyk M 2010 *Inter. Agrophysics* **24** 369–374
[23] Nursyamsi D, Noor M and Maftu'ah E 2016 *Peatland Management for Sustainable Agriculture Tropical Peatland Ecosystems* ed M Osaki and N Tsuji (Tokyo: Springer Japan) p 493–511