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EXPLORING SOIL FERTILITY VARIATIONS UNDER NEPHROLEPIS BISERRATA IN MULTI-SOIL TYPE OF OIL PALM PLANTATIONS

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ABSTRACT

Objective: The aim of this study was to analyze the physical and chemical properties of soil under *Nephrolepis biserrata* as a ground cover crop in oil palm plantations on Ultisols, Spodosols, and Histosols.

Theoretical Framework: The research design comprehensively outlines the procedures for conducting the study, including data sources, collection methods, and analysis techniques, ensuring clarity in describing variables and facilitating effective data collection and analysis.

Method: The study design used a splitplot with the main plot on soil types (Ultisols, Spodosols, Histosols) and subplots on cover crop conditions (without cover crop, *N. biserrata*, various cover crops) covering an area of 180 ha.

Results: The research findings demonstrate that the use of cover crops significantly improves both the physical and chemical properties of soil in oil palm plantations. Notably, cover crops effectively enhance various chemical properties, such as pH, organic carbon, total nitrogen, phosphorus, and exchangeable cations, across different soil types. Even in Histosols with naturally high nutrient levels, implementing cover crops yields substantial benefits, particularly in pH improvement and nutrient enrichment.

Research Implications: *N. biserrata* demonstrated better results compared to different cover crops. However, it's crucial to carefully select appropriate cover crops to improve soil quality and support the growth of oil palm plantations, considering the specific soil type.

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Originality/Value: This research, focusing on the physical and chemical properties of soil under *N. biserrata* in Indonesian oil palm plantations, serves as a valuable reference for companies seeking to select the most suitable ground cover plants tailored to their soil types.

Keywords: Oil Palm, Cover Crops, *N. Biserrata*, Soil Types, Mature Palm.

EXPLORANDO AS VARIAÇÕES DE FERTILIDADE DO SOLO SOB NEPHROLEPIS BISERRATA EM PLANTAÇÕES DE PALMEIRAS DE ÓLEO DO TIPO MULTISOLO

RESUMO

Objetivo: O objetivo deste estudo foi analisar as propriedades físicas e químicas do solo sob *Nephrolepis biserrata* como uma cultura de cobertura do solo em plantações de palmeiras de óleo em Ultisols, Spodosols e Histosols.

Estrutura Teórica: O desenho da pesquisa descreve de forma abrangente os procedimentos para a realização do estudo, incluindo fontes de dados, métodos de coleta e técnicas de análise, garantindo clareza na descrição de variáveis e facilitando a coleta e análise de dados eficazes.

Método: O projeto do estudo utilizou uma parcela divisória com a parcela principal em tipos de solo (Ultisóis, Spodosóis, Histossóis) e subparcelas em condições de cultivo de cobertura (sem cultura de cobertura, *N. biserrata*, várias culturas de cobertura) cobrindo uma área de 180 ha.

Resultados: Os resultados da pesquisa demonstram que o uso de culturas de cobertura melhora significativamente as propriedades físicas e químicas do solo em plantações de dendê. Notavelmente, as culturas de cobertura efetivamente melhoram várias propriedades químicas, como pH, carbono orgânico, nitrogênio total, fósforo e cátions permutáveis, em diferentes tipos de solo. Mesmo em Histosóis com níveis de nutrientes naturalmente elevados, a implementação de culturas de cobertura produz benefícios substanciais, particularmente na melhoria do pH e no enriquecimento de nutrientes.

Implicações da pesquisa: *N. biserrata* demonstrou melhores resultados em comparação com diferentes culturas de cobertura. No entanto, é fundamental selecionar cuidadosamente as culturas de cobertura adequadas para melhorar a qualidade do solo e apoiar o crescimento das plantações de palmeiras de óleo, considerando o tipo específico de solo.

Originalidade/valor: Esta pesquisa, focada nas propriedades físicas e químicas do solo sob *N. biserrata* em plantações indonésias de palmeiras de óleo, serve como uma referência valiosa para empresas que buscam selecionar as plantas de cobertura terrestre mais adequadas para seus tipos de solo.

Palavras-chave: Óleo de Palma, Culturas de Cobertura, *N. Biserrata*, Tipos de Solo, Palma Madura.

EXPLORAR VARIACIONES DE FERTILIDAD DEL SUELO BAJO NEPHROLEPIS BISERRATA EN PLANTACIONES DE PALMA ACEITERA DE TIPO MULTISUELO

RESUMEN

Objetivo: El objetivo de este estudio fue analizar las propiedades físicas y químicas del suelo bajo *Nephrolepis biserrata* como cultivo de cobertura vegetal en plantaciones de palma aceitera en Ultisols, Spodosols e Histosols.

Marco teórico: El diseño de la investigación describe exhaustivamente los procedimientos para realizar el estudio, incluidas las fuentes de datos, los métodos de recopilación y las técnicas de análisis, garantizando la claridad en la descripción de las variables y facilitando la recopilación y el análisis efectivos de datos.

Método: El diseño del estudio utilizó una parcela dividida con la parcela principal en tipos de suelo (Ultisols, Spodosols, Histosols) y subparcelas en condiciones de cultivo de cobertura (sin cultivo de cobertura, *N. biserrata*, varios cultivos de cobertura) que cubren un área de 180 ha.

Resultados: Los resultados de la investigación demuestran que el uso de cultivos de cobertura mejora significativamente las propiedades físicas y químicas del suelo en las plantaciones de aceite de palma. En particular, los cultivos de cobertura mejoran efectivamente varias propiedades químicas, como el pH, el carbono orgánico, el nitrógeno total, el fósforo y los cationes intercambiables, en diferentes tipos de suelo. Incluso en

histosoles con niveles naturalmente altos de nutrientes, la implementación de cultivos de cobertura produce beneficios sustanciales, particularmente en la mejora del pH y el enriquecimiento de nutrientes.

Implicaciones de la investigación: *N. biserrata* demostró mejores resultados en comparación con diferentes cultivos de cobertura. Sin embargo, es crucial seleccionar cuidadosamente los cultivos de cobertura adecuados para mejorar la calidad del suelo y apoyar el crecimiento de las plantaciones de aceite de palma, teniendo en cuenta el tipo de suelo específico.

Originalidad/Valor: Esta investigación, que se centra en las propiedades físicas y químicas del suelo bajo *N. biserrata* en las plantaciones de aceite de palma de Indonesia, sirve como una referencia valiosa para las empresas que buscan seleccionar las plantas de cobertura del suelo más adecuadas adaptadas a sus tipos de suelo.

Palabras clave: Palma Aceitera, Cultivos de Cobertura, *N. Biserrata*, Tipos de Suelo, Palma Madura.

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1 INTRODUCTION

Comprehension the characteristics of multi-soil types in oil palm plantations is crucial to support plant growth and sustainable productivity enhancement. The use of cover crops has been recognized as an effective soil management strategy for improving soil fertility. These cover crops not only have the potential to enrich the soil with organic material, howeveralso improve the physical and chemical properties of the soil through increased nutrient availability and soil structure improvement. Regarding the oil palm during its mature phase (MP), new challenges arise, such as the need to replace legume cover crops (LCC) with efficient alternative cover crops. *Nephrolepis biserrata* offers a potential solution to these challenges and is anticipated to effectively replace LCC due to its ability to enrich the soil with organic material, thereby improving the soil's physical and chemical properties.

N. biserrata is an invasive species commonly found in oil palm plantations (Awmpuia & Lalruatsanga, 2021). This plant grows well in less fertile soils (Samedani et al. 2013) and under closed canopy conditions (Adeleye et al., 2016; Satriawan & Fuady, 2014). It is known to have a moderate capacity for metal accumulation and antioxidant properties, making it a potential phytoremediation agent for metals in contaminated soils (Manan et al., 2015). This aligns with the report by laporan Ancheta et al. (2020) that *N. biserrata*, along with *Cynodon dactylon* and *Pityrogramma calomelanos*, can tolerate heavy metals and are potential candidates for phytostabilization of contaminated soils. *Nephrolepis biserrata* contains phytochemicals with antioxidant and vermicidal properties, howeverit is not effective as a

bactericide (Brice & Yves-Alain, 2021). Supriyanto et al., (2022) added that *Nephrolepis biserrata* is very effective in managing vegetation on peatlands to control Ganoderma diseases.

N. biserrata be able to accumulate nitrogen (N) nutrients at 1.23-1.53%, phosphorus (P) at 0.18-0.22%, and potassium (K) at 1.4-1.67% with a total dry biomass of 27.1 tons/ha, carbon (C) accumulation of 0.9 tons/ha/year, and soil carbon stocks between 76.4 - 97.4 tons/ha/year (Satriawan et al., 2021). Saputra et al. (2023) revealed that the plant density of *N. biserrata* has a significant impact on the percentage of coverage and the dry weight of oil palm roots, where a denser density produces better microclimate conditions compared to medium or low density. The application of empty fruit bunches and good management of *N. biserrata* vegetation can reduce the impact of drought and increase oil palm production by 15% in sandy soils (Gunawan et al., 2020). Murtilaksono et al. (2018) demonstrated that terrace management and *N. biserrata* cover crops significantly reduce surface runoff and soil erosion in oil palm plantations, with cover crops being more effective than control terraces. Ariyanti et al. (2015) also reported that *N. biserrata*, as a cover crop in combination with terraces, could increase groundwater reserves by approximately 71% and reduce water loss by 36% and 80%, respectively. Additionally, the presence of *N. biserrata* shortens the water deficit period by up to 50 days compared to terracing alone (Ariyanti et al., 2016).

Based on previous study, expertise about the specific interactions between multi-soil types and cover crops is still limited, especially in the context of oil palm plantations. The aim of this study was to analyze the physical and chemical properties of soil in oil palm plantations, with a focus on the use of *N. biserrata* as a ground cover crop. One innovative aspect of this research is the exploration of the organic material content produced by *N. biserrata* in the majority soil types found in oil palm plantations, namely Ultisols, Spodosols, and Histosols.

2 THEORETICAL FRAMEWORK

This study was conducted in an oil palm plantation located in Seruyan District, Central Kalimantan Province, Indonesia. The research area occupies mostly flat terrain, partially including slightly undulating areas, with altitudes ranging from 5 to 32 m above sea level. The Ultisols used in this study include the Aquic Paleudults and Typic Paleudults series. Spodosols use the Typic Haplohumods soil series, whereas Histosols use the Typic Haplohemist.

3 METHODOLOGY

3.1 PROCEDURE

This study was comparative research using a splitplot design, where soil type (T) was the main plot and cover crop (C) was the subplot. The soil type factor (T) included Ultisols (T1), Spodosols (T2), and Histosols (T3), whereas the cover crop factor consisted of a block without cover crops (C1), a block with *N. biserrata* cover crops (C2), and a block with various cover crops (C3). Based on these combinations, there were 9 treatments. Each treatment had 6 replications, resulting in 54 experimental units. Each treatment block covered an area of 20 ha, totaling 180 ha of oil palm plantation area. The ages of the oil palm plants ranged from 13 to 15 years. Soil samples were collected from circle and interrow in each treatment. Soil sampling for each treatment was carried out at five different sampling points using a soil auger at a depth of 0-20 cm. Each soil sample was cleared of plant roots, composited, and placed in labeled plastic bags.

The soil samples were then air-dried, ground, and sieved using a <2.0 mm sieve to determine the physical-chemical properties of the soil. The analysis of the soil physical properties involved determining the soil texture. Chemical property analysis included measuring the pH, C C organicontent, total N, total P, P-Bray, and the content of exchangeable potassium, magnesium, calcium, and sodium (Exc-K, Exc-Mg, Exc-Ca, and Exc-Na). Additionally, Cation Exchange Capacity (CEC) and Base Saturation (BS) were measured to assess the capacity of the soil to retain and exchange cations, and the proportion of CEC occupied by base cations.

3.2 DATA ANALYSIS

Analysis of variance (ANOVA) was performed to observe the effects of the treatments on the measured parameters. Bartlett's test and Shapiro-Wilk test were conducted on all observed parameters before ANOVA to ensure all data had homogeneous variance and normal distribution. In the event that ANOVA results demonstrated significant effects, descriptive data analysis was also carried out by comparing the soil test data from the laboratory with the soil fertility evaluation standards, as shown in Table 1.

Table 1

Soil fertility evaluation criteria for oil palm

Properties	Reference	*Very Low*	*Low*	*Moderate*	*High*	*Very High*
pH	1	< 3,5	4	4,2	5,5	> 5,5
C Organic (%)	1	< 0,8	1,2	1,5	2,5	> 2,5
Total N (%)	1	< 0,08	0,12	0,15	0,25	> 0,25
Total P (%)	1	< 120	200	250	400	> 400
P Bray (ppm)	1	< 8	15	20	25	> 25
Exc-K (meq/100g)	1	< 0,08	0,2	0,25	0,30	> 0,30
Exc-Mg (meq/100g)	1	< 0,08	0,2	0,25	0,30	> 0,30
Exc-Ca (meq/100g)	2	< 2	2-5	6-10	11-20	> 20
Exc-Na (meq/100g)	2	< 0,1	0,1-0,3	0,04-0,7	0,8-1,0	> 1,0
CEC (meq/100g)	1	< 6	12	15	18	> 18
BS (%)	2	< 20	20-40	41-60	61-80	81-100

Source: 1. Goh Kah Joo, 1997, 2. Balittanah, 2011

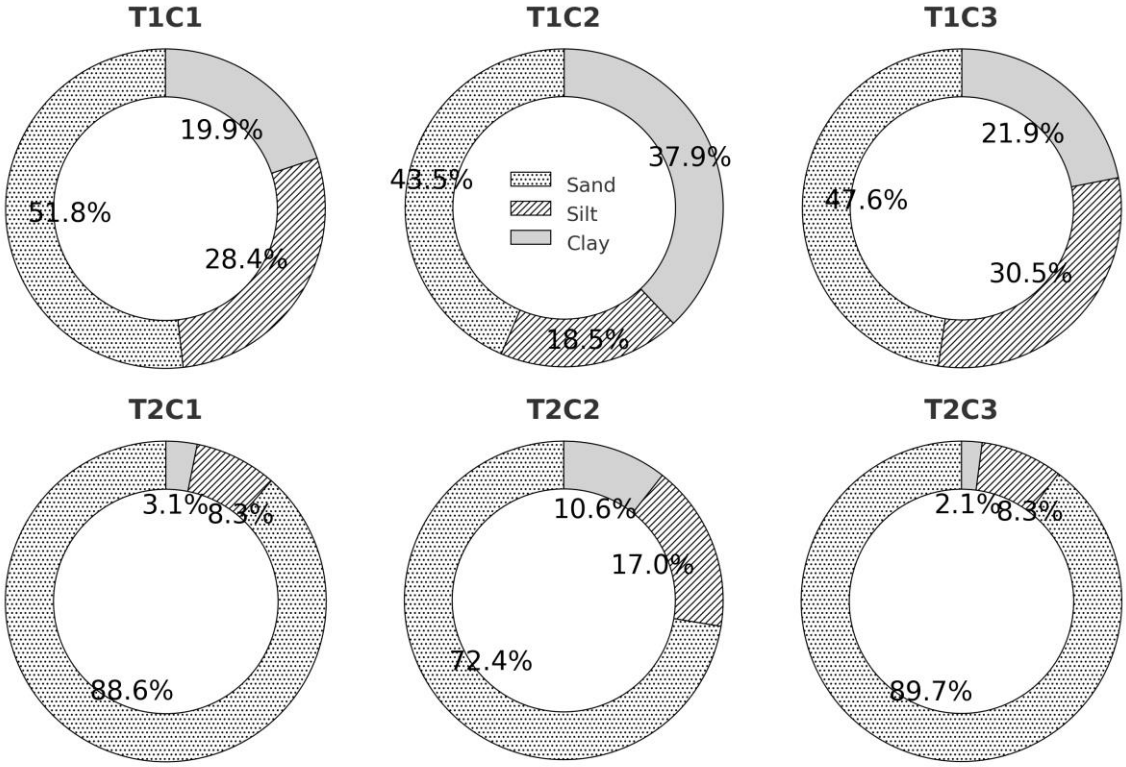
4 RESULTS AND DISCUSSIONS

4.1 RESULTS

The analysis of the physical properties of Ultisols shown in Figure 1 indicates that the soil without cover crops (T1C1) has a composition of 51.77% sand, 28.36% silt, and 19.87% clay (sandy loam texture). The soil with *N. biserrata* (T1C2) was composed of 43.53% sand, 18.53% silt, and 37.94% clay or clayey sandy loam. In the treatment with various cover crops (T1C3), the soil texture consisted of 47.63% sand, 30.46% silt, and 21.91% clay or sandy loam. Spodosols without cover crops (T2C1) were composed of 88.57% sand, 8.29% silt, and 3.14% clay (sandy texture). Spodosols with *N. biserrata* (T2C2) have 72.40% sand, 16.98% silt, and 10.61% clay or sandy clay loam. Meanwhile, Spodosols with various cover crops (T2C3) demonstrated a very high sand composition (89.68%), with 8.25% silt and 2.06% clay or sandy texture (Figure 1).

Figure 1

Comparison of soil texture based on cover crop conditions on the parameters of soil physical properties. T1= Ultisols, T2 = Spodosols, T3 = Histosols, C1= without cover crops, C2= cover crop N. biserrata, and C3= various cover crops



Source: Prepared by Authors (2024)

Peat soil, categorized as Histosols, is fundamentally different from mineral soils (Ultisols) owing to its dominance of organic material. Its formation through the accumulation of organic material in moist and anaerobic environments results in soils with unique characteristics that do not fit the standard soil texture categorization. In peat soil, the high proportion of organic material and water content are the main factors determining its physical and chemical properties, making the use of categories such as sand, silt, and clay less relevant or indeed inapplicable in soil analysis or research, which is often not recorded in soil texture measurements for peat soils. This study provides a rationale for why soil texture analysis was not conducted on Histosols.

Table 2

Univariate analysis of variance results for the main plot (soil type) and subplot (cover crops)

No	Chemical Properties	Univariate analysis of variance		
		Soil Types (T)	Cover crops ©	Soil Types vs Cover crops
1	pH	0.005**	<0.001**	0.036*
2	C organic	<0.001**	<0.001**	<0.001**
3	Total N	<0.001**	0.065ns	0.002**
4	P Bray	0.006**	<0.001**	0.021*
5	Total P	<0.001**	0.016*	0.015*
6	Exc-K	0.003**	<0.001**	<0.001**
7	Exc-Mg	<0.001**	<0.001**	0.017*
8	Exc-Ca	<0.001**	<0.001**	<0.001**
9	Exc-Na	0.014*	<0.001**	0.023*
10	CEC	0.014*	<0.001**	0.023*
11	KB	<0.001**	<0.001**	<0.001**

*Note: ns = non-significant, * = significant at P value ≤0.05), ** = significant at P value ≤0.01*
Source: Prepared by Authors (2024)

The Univariate analysis of variance results for soil types demonstrated that almost all parameters exhibited highly significant differences (**) among different soil types, except for Exc-Na and CEC, which demonstrated significant influences (Table 2). This indicates that soil type has a major impact on the chemical characteristics of the soil. In terms of cover crop availability, only Total N did not show significant differences (ns), while almost all others demonstrated significant effects (*). The interaction results between soil types and cover crops demonstrated significant differences in all tested parameters, as presented in Table 2. This demonstrates that specific combinations of soil type and cover crop had a strong influence on the values of these chemical property parameters.

The analysis of chemical soil properties shown in Figure 3 indicates that there were variations in pH values among treatments based on fertility levels. The pH values in Ultisols are high in all treatments, howeverT1C1 (without cover crops) shows a lower pH (4.94) compared to T1C2 (5.19) and T1C3 (5.14). The best pH was found in T1C2, the Ultisols block with established *N. biserrata*, although the difference was not very high compared to T1C3 (various cover crops). The pH increase in T1C2 indicates the positive potential of *N. biserrata* in improving the pH levels of Ultisols. In Spodosols, the pH is in the medium to high category, with the lowest value at 4.15 (T2C1) and the highest pH at 4.43 (T2C2). This indicates that the use of *N. biserrata* (T2C2) also has a positive impact on improving the pH of Spodosols. Meanwhile, in Histosols, there was an increase in pH in T3C2 with a pH of 4.18 (medium) and T3C3 with a pH of 4.32 (high) compared to the control T3C1 with a pH of 3.86 (low). This increase shows that cover crops, both *N. biserrata* and various other cover crops, can contribute positively to the improvement of pH in Histosols.

The content of C organic in all treatments on Ultisols was high, with T1C1 (2.30%) showing a lower level than T1C2 (9.28%) and T1C3 (6.24%). The increase in C organic in T1C2 demonstrates the effectiveness of *N. biserrata* cover crops in enhancing soil C organic content. In Spodosols, although the increase in C organic is not as significant as in Ultisols, there is still a positive effect from using cover crops. T2C2 (with *N. biserrata*) shows an C organic of 3.00%, which is higher than T2C1 (2.17%) and T2C3 (1.58%). In Histosols, the C organic content was very high under all conditions, with the highest value at T3C1 (46.80%), followed by T3C2 (35.56%) and T3C3 (29.16%). This indicates that Histosols naturally have a very high C organic content, and the use of cover crops has a more limited impact on increasing C organic in this type of soil. However, looking at the C/N ratio parameter, the presence of cover crops (T3C2 24.90, T3C3 24.96) performed better than without cover crops (29.43).

Total N in Ultisols shows differences between T1C1 at 0.16% (high), T1C2 at 0.44% (very high), and T1C3 at 0.34% (very high). This indicates that using *N. biserrata* as a cover crop is very effective in increasing nitrogen content in Ultisols, likely because of its contribution to improving soil structure and fertility. In Spodosols, Total N also demonstrated an increase in treatments using cover crops. In T2C1 (without cover crops), the Total N content was 0.13% (moderate), T2C2 (with *N. biserrata*) was 0.23%, and T2C3 (various cover crops) was 0.17%. This shows that cover crops have a positive effect on nitrogen content, although the increase is not as significant as that in Ultisols. In contrast, in Histosols, Total N is already very high without cover crops (1.59%), and remains very high although lower in T3C2 (1.43%) and T3C3 (1.17%). This indicates that Histosols naturally have a high nitrogen content, and the use of cover crops has not increased.

The P Bray in Ultisols ranged from low to moderate. Without cover crops (T1C1), P Bray is recorded at 10.61 ppm (low), whereas the use of *N. biserrata* (T1C2) at 17.39 ppm and various cover crops (T1C3) at 15.94 ppm fall within the moderate category. This indicates that the use of *N. biserrata* has a positive impact on phosphorus availability in Ultisols. In Spodosols, there was an increase in P Bray content between treatments without cover crops and those using cover crops. Without cover crops (T2C1), P Bray is only 11.64 ppm (low), whereas with *N. biserrata* (T2C2) it is significantly higher at 86.29 ppm (very high), and T2C3 at 33.10 ppm (high). This demonstrates the strong effect of cover crops on increasing phosphorus availability in Spodosols. In Histosols, the P Bray content ranges more widely. T3C1 (without cover crops) has a P Bray content of 14.26 ppm (low), whereas the use of *N. biserrata* (T3C2, 89.46 ppm) and various cover crops (T3C3, 98.14 ppm) are categorized as very high. This indicates that both *N. biserrata* and various cover crops are highly effective in increasing

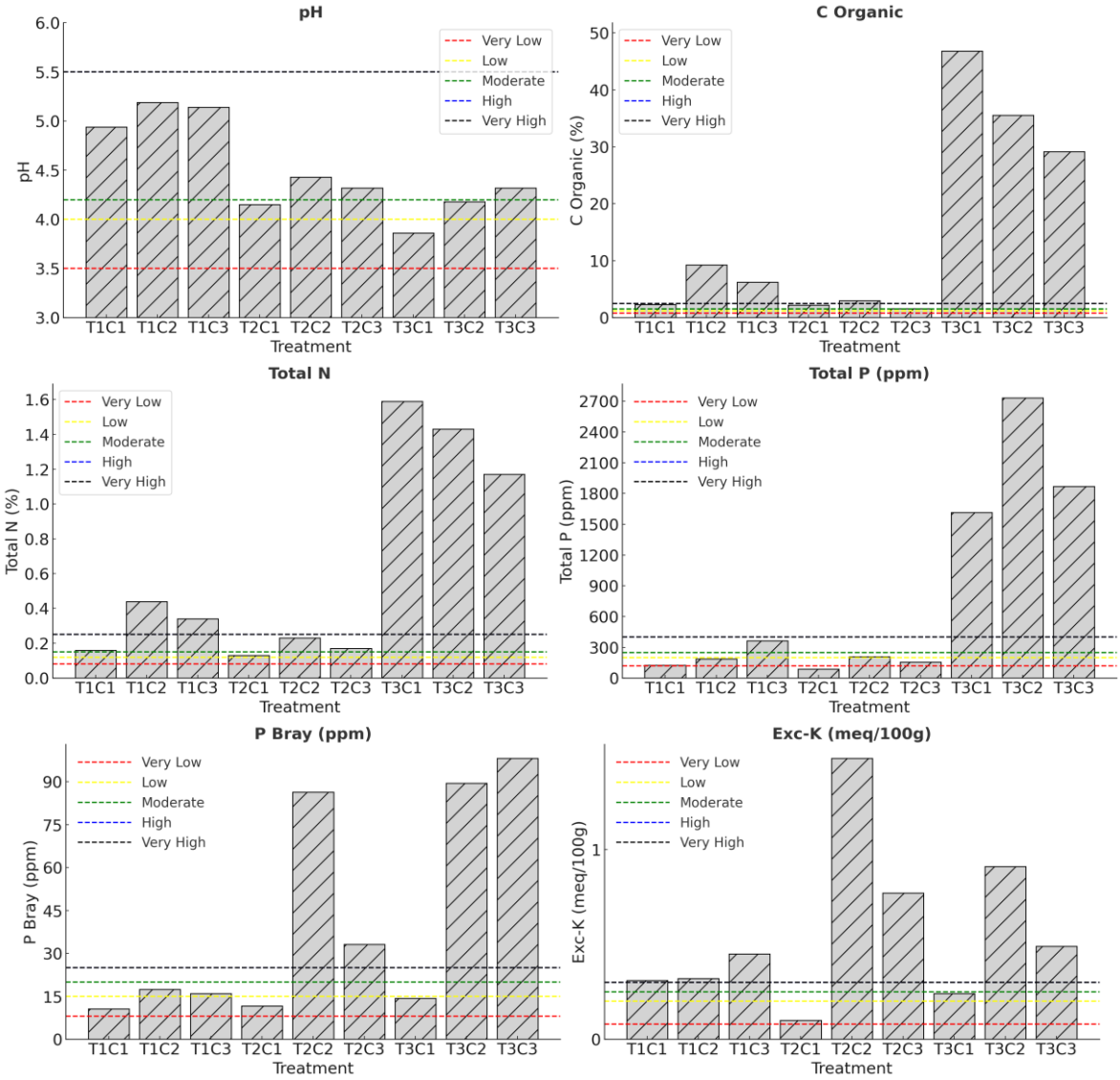
phosphorus availability in Histosols.

Exc-K in Ultisols is very high in all treatments, with a value of 0.31 meq/100g in T1C1 (without cover crops), 0.32 meq/100g in T1C2 (with *N. biserrata*), and 0.45 meq/100g in T1C3 (various cover crops). This indicates that Ultisols naturally have high Exc-K, and the application of cover crops, both *N. biserrata* and various others, maintains very high potassium levels. In Spodosols, the Exc-K content varies. Without cover crops (T2C1), Exc-K is low at 0.10 meq/100 g. However, in treatments with *N. biserrata* cover crops (T2C2), Exc-K was very high (1.48 meq/100 g). In T2C3 (various cover crops), Exc-K is also classified as very high at 0.77 meq/100 g. This demonstrates the effectiveness of cover crops in increasing K availability in Spodosols. Meanwhile, in Histosols, Exc-K levels range from moderate to very high. In T3C1 (without cover crops), potassium content is moderate (0.24 meq/100 g). With the use of *N. biserrata* (T3C2), Exc-K content increases to very high (0.91 meq/100 g), as well as in T3C3 (0.49 meq/100 g) with various cover crops.

Exc-Mg in Ultisols without cover crops (T1C1) is 0.14 meq/100 g (low), which is lower compared to the block with *N. biserrata* cover crops (T1C2) at 0.26 meq/100 g (high) and various cover crops (T1C3) at 0.61 meq/100 g (very high). This increase indicates the effectiveness of cover crops, particularly various cover crops, in enhancing magnesium availability in Ultisols. In Spodosols, the Exc-Mg content also demonstrated differences between treatments. In the block without cover crops (T2C1), Exc-Mg content is 0.08 meq/100 g (low), which is lower compared to T2C2 at 0.42 meq/100 g (very high) and T2C3 at 0.30 meq/100 g (high). This indicates that the application of cover crops, especially *N. biserrata*, plays a key role in increasing the magnesium content in Spodosols. Meanwhile, in Histosols, Exc-Mg content was high in all treatments, with the lowest value in T3C1 (0.85 meq/100 g, very high) and the highest in T3C3 (1.03 meq/100 g, very high). These results show that Histosols naturally have a high magnesium content, and the use of cover crops assist maintain this level.

Figure 2

Comparison of soil nutrient levels based on cover crop conditions on parameters pH, C Organic, Total N, Total P, P Bray, and Exc-K



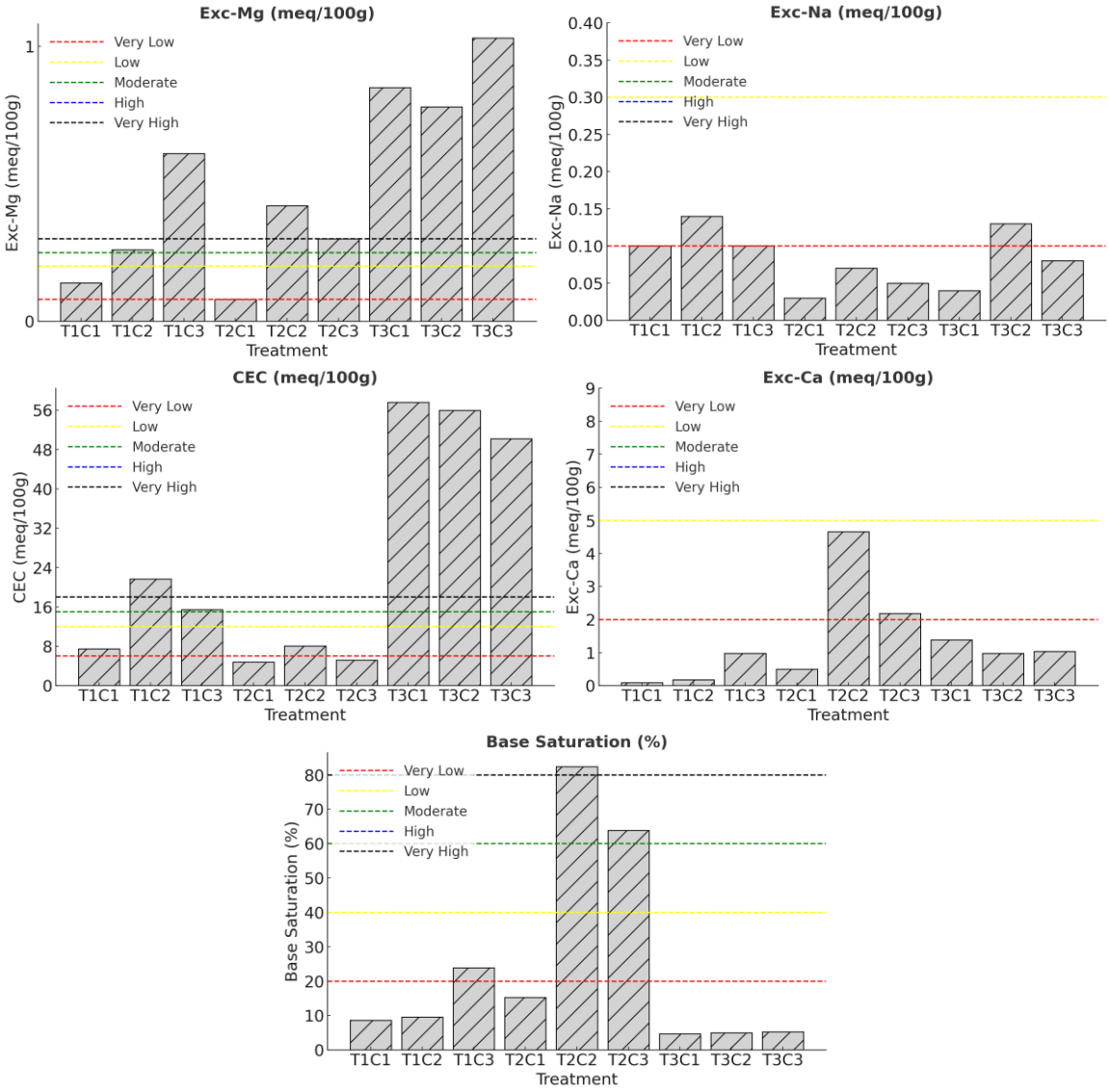
Source: Prepared by Authors (2024)

Overall, Exc-Ca in Ultisols is very low. Without cover crops (T1C1), Exc-Ca content is only 0.09 meq/100 g, although there is an increase with the application of *N. biserrata* (T1C2) to 0.18 meq/100 g and various cover crops (T1C3) increase the content to 0.98 meq/100 g, both are still in the very low category. In Spodosols, there was a greater increase in Exc-Ca content with the use of cover crops. Without cover crops (T2C1), Exc-Ca content is 0.50 meq/100 g. In blocks using *N. biserrata* (T2C2), Exc-Ca content is higher (4.66 meq/100 g) and with various cover crops (T2C3) is 2.18 meq/100 g, howeverstill considered low. This indicates that the use of cover crops can increase calcium availability in this soil. In Histosols, Exc-Ca content is in

the same range, with the highest value in T3C3 (1.03 meq/100 g),howeverall are still in the very low category. Although there was variation between treatments, the Exc-Ca content generally remained low in Histosols.

Figure 3

Comparison of soil nutrient levels based on cover crop conditions for parameters Exc-Mg, Exc-Ca, Exc-Na, CEC, and Base Saturation



Source: Prepared by Authors (2024)

Exc-Na in Ultisols, shown in Figure 3, was consistently low in all treatments. The treatment without cover crops (T1C1) had an Exc-Na content of 0.10 meq/100g. The application of *N. biserrata* (T1C2) is only slightly higher at 0.14 meq/100 g, while with various cover crops (T1C3) it is lower at 0.10 meq/100 g. This shows that the use of cover crops in

Ultisols has minimal influence on Exc-Na content. In Spodosols, Exc-Na content is at a very low level, ranging from 0.03 meq/100 g without cover crops (T2C1) to 0.07 meq/100 g with *N. biserrata* (T2C2) and 0.05 meq/100 g with various cover crops (T2C3). Although there was an increase with the application of *N. biserrata*, the Exc-Na content remained in a very low range. Exc-Na content in Histosols was also very low, with little variation between treatments. The treatment without cover crops (T3C1) had 0.04 meq/100 g, while with *N. biserrata* (T3C2) it was slightly higher at 0.13 meq/100 g, and T3C3 (with various cover crops) at 0.08 meq/100 g.

There is an increase in CEC in Ultisols from the treatment without cover crops (T1C1), which has a CEC value of 7.48 meq/100 g (low), compared to the use of *N. biserrata* (T1C2) which shows 21.67 meq/100 g (very high) and 15.46 meq/100 g (high) with various cover crops (T1C3). This increase indicates that the application of cover crops, especially *N. biserrata*, plays a crucial role in enhancing CEC in Ultisols, demonstrating the increased potential of the soil to supply cationic nutrients. In Spodosols, the CEC values are generally lower. Without cover crops (T2C1), the CEC is very low at 4.80 meq/100 g. Although there was an increase to 8.05 meq/100 g (low) with *N. biserrata* (T2C2) and 5.16 meq/100 g (very low) with various cover crops (T2C3), these values remained relatively low and indicated the soil's limitations in providing and retaining cationic nutrients. CEC values in Histosols were very high in all treatment conditions, with the lowest at T3C1 (57.59 meq/100 g) and the highest at T3C2 (55.94 meq/100 g), all categorized as very high. This indicates that Histosols naturally have an excellent capability to retain and supply cationic nutrients.

Base Saturation (KB) in Ultisols tends to be very low, with slight improvements in blocks with cover crops. The KB rate in the block without cover crops (T1C1) was 8.59% (very low). The use of *N. biserrata* (T1C2) demonstrated a higher result of 9.61% (very low), while various cover crops (T1C3) demonstrated an increase to 23.88% (low). This improvement indicates that cover crops, especially diverse ones, can slightly enhance the capacity of the soil to retain base cations. KB in Spodosols shows greater variation. Without cover crops (T2C1), KB was recorded at 15.32% (very low),howeverwith *N. biserrata* (T2C2), it increased drastically to 82.38% (very high), and with various cover crops (T2C3), it increased to 63.87% (high). This remarkable increase indicates that cover crops have a positive impact on increasing base saturation in Spodosols. Meanwhile, KB in Histosols remained very low in all treatment conditions, ranging from 4.68% to 5.22%. This indicates that Histosols naturally have a low capacity to retain base cations.

4.2 DISCUSSION

Theoretically, soil texture (composition/proportion of sand, silt, and clay content) is not influenced by vegetation, including cover crops. Logically, sand has never transformed into silt or clay over a span of 20 years. Therefore, soil texture parameters are never used as physical properties that are influenced by treatments. However, texture measurements are still performed to provide an overview that the soil used in research on Ultisols ranges from loamy to sandy loam, whereas in Spodosols, it ranges from sandy to sandy loam. This also influences the chemical properties of the soil.

Based on the results of the univariate analysis of variance, there are several important aspects to note. First, the type of soil plays a crucial role, as it affects changes in all chemical properties of the soil. This indicated that each soil type had unique chemical characteristics. Second, the use of cover crops has been proven to influence changes in soil chemical properties (except Total N and Total P), although its impact is not as strong as the soil type factor. Third, the interaction between soil type and cover crops has been proven to result in differences in most soil chemical properties (except pH and Total P). This indicates that the effects of cover crops on soil chemical properties can vary depending on the existing soil type.

The analysis of physical properties shows that the soil texture composition varies between Ultisols and Spodosols, it is also influenced using cover crops. The use of *N. biserrata* in Ultisols assist increase the clay proportion, which can affect the physical and chemical properties of the soil, including its capacity to retain water and nutrients. In Spodosols, although there is variation in the proportions of sand, silt, and clay, the dominant sand characteristics remain consistent, indicating limitations in the soil's capacity to retain water and nutrients. However, in Spodosols, the use of cover crops demonstrated better results through an increase in clay content.

Comparative analysis of soil chemical properties demonstrated that the use of *N. biserrata* as a cover crop contributed positively to improving the pH value of the soil in the three soil types studied. Ultisols demonstrated relatively high pH values under all conditions, indicating stability in terms of soil chemical properties. In Spodosols, the use of *N. biserrata* has proven effective in increasing pH values, demonstrating its ability to improve the chemical properties of acidic soil. Meanwhile, in Histosols, the increase in pH from low to high in cover crop treatments shows great potential for rehabilitating highly acidic soils. Overall, these data confirm that the use of cover crops, particularly *N. biserrata*, can be an effective strategy to improve soil chemical properties in oil palm plantations (Figure 4), with an increase in pH value

as the primary indicator.

Overall, C organic shows that the use of *N. biserrata* as a cover crop increases C organic content in Ultisols and Spodosols. In Ultisols, the increase in C organic is particularly notable with the use of *N. biserrata*. In Spodosols, the effect was more moderate, howeverstill positive. On the other hand, Histosols naturally show very high C organic content, with little variation among cover crop treatments. This result affirms the potential of *N. biserrata* to improve soil quality, especially in soils with lower C organic content, and highlights the importance of choosing the right cover crops according to soil type for optimizing soil chemical properties in oil palm plantations. However, based on the C/N ratio analyzed, the use of *N. biserrata* or various cover crops demonstrated better results. In terms of Total N, the use of *N. biserrata* is very effective in increasing the Total N content in Ultisols and Spodosols. This increase demonstrates the great potential of *N. biserrata* in improving soil fertility, especially in soils with an initially lower nitrogen content. Conversely, Histosols naturally show a very high nitrogen content, and the use of cover crops does not substantially change this condition.

Total P demonstrated that the use of cover crops had varying influences on the total phosphorus content in the soil. In Ultisols, diverse cover crops demonstrated the highest effectiveness in increasing phosphorus content. In Spodosols, the use of *N. biserrata* moderately increased the phosphorus content. Meanwhile, in Histosols, the phosphorus content is already very high and the use of cover crops does not cause a change. These results highlight the importance of considering soil type and selecting the appropriate type of cover crop in efforts to enhance soil nutrient content, particularly phosphorus, to optimally support the growth of oil palm plants. The P Bray analysis results demonstrated that the use of cover crops, especially *N. biserrata*, had an impact on increasing phosphorus availability (P Bray) in the soil, especially in Spodosols and Histosols. This increase in phosphorus availability is crucial for the growth of oil palm plants, given that phosphorus is a key nutrient supporting plant development.

The use of cover crops tends to increase the content of exchangeable potassium (Exc-K) and exchangeable magnesium (Exc-Mg) in the soil. This increase occurred because cover crops contribute significantly to enhancing potassium availability. In Ultisols, although the potassium content is already very high naturally, the use of cover crops still contributes to the maintenance of very high potassium levels. In Histosols, the use of cover crops, both *N. biserrata* and other diverse types, also increases the potassium content. In the Exc-Mg parameter, the highest increase was found in Ultisols and Spodosols, showing that cover crops can play an important role in enhancing soil fertility in these soil types. In Histosols, although

the magnesium content is already naturally high, the use of cover crops still provides benefits in maintaining high magnesium levels.

The Exc-Ca content tended to be very low in all treatments, although there was an increase with the use of cover crops, especially in Spodosols. This indicates that although cover crops such as *N. biserrata* can contribute to increasing the availability of calcium in the soil, the effect varies depending on the soil type. These results also highlight the challenges of increasing Exc-Ca content in soils with naturally very low levels, indicating the need for more focused fertilization and soil management strategies. This was also the case with the Exc-Na content, which was generally low in all studied soil types, although there was a slight increase in some treatments. However, this increase was not significant enough to indicate that cover crops had a major impact on increasing the content of exchangeable sodium. This suggests that other factors, such as the intrinsic characteristics of the soil or other soil management practices, may play a more dominant role in determining Exc-Na content.

One important soil fertility parameter is CEC, which indicates that soil type and the use of cover crops have a significant influence on soil CEC values. In Ultisols, the use of cover crops, especially *N. biserrata*, enhances CEC. In Spodosols, although cover crops contributed to an increased CEC, the values remained relatively low. Histosols naturally exhibit a very high CEC, with little variation between cover crop treatments. Base saturation (BS) results indicate that the use of cover crops, particularly *N. biserrata*, can increase BS, especially in Spodosols. The use of various cover crops in Ultisols shows an increase in BS, although it is still in the low category. However, BS in Histosols remained very low, regardless of the cover crop treatments applied.

Overall, the soil chemical property analysis revealed variations in pH values between treatments with vegetation cover crops. Ultisols displayed high pH across all treatments, with the most significant increase in blocks with *N. biserrata*. In Spodosols, *N. biserrata* also enhances pH, whereas in Histosols, cover crops increase the pH from low to medium or high. The data also demonstrate the effectiveness of *N. biserrata* in increasing C organic content, particularly in Ultisols and Spodosols, whereas in Histosols, it is naturally high. Total N increases in Ultisols and Spodosols with the use of *N. biserrata*, whereas Histosols have naturally high nitrogen content. Total P and P Bray improved with cover crops, particularly in Ultisols and Spodosols, showing the potential of cover crops to enhance phosphorus content. Exchangeable potassium and magnesium contents increase in Spodosols with the use of cover crops, especially *N. biserrata*, whereas Ultisols and Histosols are naturally high. Exchangeable calcium and sodium contents were generally low in all soil types, although there was an

improvement with cover crops. CEC increased with the use of *N. biserrata* in Ultisols, demonstrating its potential to enhance soil capacity to provide nutrients. However, CEC values remained relatively low in Spodosols and very high in Histosols across all treatments. Base saturation (BS) increases with the use of cover crops, particularly Spodosols, howeverremains low in Histosols. This indicates the need for the selection of cover crops and soil management appropriate for specific soil characteristics.

The analysis results show that the application of cover crops plays a crucial role in increasing soil pH and C organic. Plant residues can increase soil pH through the decarboxylation of organic anions, excess bases, and nitrification, among other mechanisms (Zhi, 2005). The use of cover crops has been reported to contribute to increasing soil pH (Fageria et al., 2009, 2014) through root mechanisms that transport nutrients from the subsoil layers to the surface, thereby aiding in the pH balancing process. Högberg et al., (2006) disclose that soil pH can increase or decrease due to the transportation of basic cations and nitrogen, affecting the allocation of plant C underground to roots and mycorrhizal fungi. Rukshana et al. (2011) added that soil pH can increase or decrease due to the addition of organic acids and potassium citrate. The application of manure be able to increase soil pH by protonating organic anions and releasing exchangeable base cations from negatively charged sites in organic matter (Shi et al., 2019). Increases in soil pH caused by amendments, particularly lime and fly ash, are associated with changes in soil enzyme activity and microbial composition, thereby reducing the acid stress in the soil (Ai et al., 2015).

In addition, cover crops be able to improve the nitrogen cycle due to increases in pH, thus potentially minimizing the need for acid-forming nitrogen fertilizers in soils, which tends to decrease soil pH (Farzadfar & Congreves, 2022; Gambart et al., 2020; Kumawat et al., 2022). The addition of nitrogen has been reported to significantly reduce soil pH by an average of 0.26 globally, with soil acidification varying by ecosystem type, level of nitrogen addition, form of fertilization, and duration of the experiment (Tian & Niu, 2015). Long-term nitrogen addition accelerates soil acidification, causing the depletion of base cations, a decrease in base saturation, and a lowering of the soil's acid neutralization capacity in tropical forests (Lu et al., 2014). Nitrogen fertilizer application in no-till agroecosystems results in little change in the soil pH and exchangeable cations (Matocha et al., 2016).

The increase in C organic is also influenced by the availability of biomass in the soil; therefore, the decomposition process of cover crops can add to soil organic matter. The decomposition activity of organic material is highly influenced by soil macrofauna and microflora, creating biological soil activity that supports the decomposition of organic matter

into humus, which is wealthy in carbon (Marshall, 2000). For example, Pseudomonas fluorescens inhibits soil acidification by forming neutral molecules with H^+, reducing the activity of H^+ in solution, and increasing the effective cation exchange capacity and exchangeable base cations of the soil (Nkoh et al., 2020). Microbes that solubilize and mobilize phosphorus, such as those from the genera Arthrobacter, Bacillus, Burkholderia, Natrinema, Pseudomonas, Rhizobium, and Serratia, can enhance plant phosphorus uptake by plants (Kour et al., 2021). Efficient rhizosphere microbes, such as rhizobacteria and fungal strains, effectively solubilize potassium and make it available to plants, contributing to a sustainable food production system (Sattar et al., 2019).

Another function of cover crops is to effectively mitigate soil erosion, preserve soil organic matter, and minimize the leaching of soil macro-and micronutrients (De Baets et al., 2011b, 2011a; Ikazaki et al., 2018). (Increases in pH and C organic in the soil have been reported to affect various soil nutrient adequacy parameters, including Total N, P Bray, Exc-K, Exc-Mg, Exc-Ca, Exc-Na, CEC, and BS (Shiri et al., 2020). Increases in pH and C organic contribute to the increase in Total N content in the soil (Li et al., 2022). High C organic also provides an additional source of nitrogen through mineralization processes. The application of high levels of C organic, such as plant residues, be able to enhance nitrogen mineralization in the soil, boosting plant nutrition (Marzi et al., 2020). High-quality C organic with high C and N contents can rapidly provide nitrogen for plants, whereas low-quality C amendments can slow down N mineralization (Bonanomi et al., 2019). Lin et al., (2016) added that high C organic in surface sediments contributes to nitrogen mineralization, a significant internal nitrogen source for water.

P Bray also increases at neutral pH levels, which can reduce phosphorus fixation by elements, such as aluminum and iron. Compost application has been reported to reduce phosphorus and exchangeable Al fixation in highly acidic soils, increasing available P by 301% (Admas et al., 2015). Organic matter also improves soil structure and enhances microbial activity, which play a role in phosphorus mineralization (Xie et al., 2022). The increase in Exc-K is due to the pH increase, which improves potassium availability and reduces its leaching. A rise in pH can also increase the Exc-K content in soil aggregates, especially in soils with an initially lower pH (Liu et al., 2020). Furthermore, an increase in exchangeable potassium (Exc-K) in the soil has been reported to enhance availability and reduce leaching, leading to improved crop yields (Jai, 2016).

Lower levels of exchangeable potassium (Exc-K) lead to a greater uptake of cesium (Cs), potentially because Exc-K is more dominant than Cs (Kubo et al., 2017). With its negative

charge, organic matter furthermore assists retain K in the soil and improve its availability (Dharmakeerthi et al., 2012). Exc-Mg and Exc-Ca can also increase with higher pH and more C organic. Higher soil pH is also associated with increased Exc-Mg status (Srinivasarao et al., 2015). Each unit decrease in soil pH from neutral can reduce Exc-Mg by twice (Ishfaq et al., 2022).

Liming significantly increases the pH index, exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}), and the soil's cation exchange capacity, whereas livestock manure increases the levels of pH, potassium (K^{+}), Ca^{2+}, and exchangeable Mg^{2+} concentration (Moreira, 2015). This is because both factors assist reduce leaching and increase the retention of these cations in the soil (Hardy et al., 2019; Ning et al., 2021). Isomorphic coprecipitation reactions with Al compounds are likely the most probable mechanism responsible for the reduction of Exc-Ca and Exc-Mg with increasing pH (Miyazawa et al., 2001). Increased pH is suspected to reduce sodium toxicity, enhance soil CEC, increase the negative charge on soil particles to retain cations, increase base saturation, and increase C organic content (Carvalho et al., 2007). The role of *N. biserrata* and other types of LCC has shown good results in improving the physical and chemical properties compared to those without the use of cover crops.

5 CONCLUSION

The employment of cover crops significantly enhances the physical and chemical characteristics of the soil in oil palm plantations. The utilization of cover crops effectively improves the chemical properties of soil, specifically in terms of pH levels (0.23), C organic (2.79%), Total N (0.15%), P Bray (27.06 ppm), Exc-K (0.55 meq/100 g), Exc-Mg (0.28 meq/100 g), Exc-Ca (1.70 meq/100 g), Exc-Na (0.03 meq/100 g), CEC (6.44 meq/100 g), and BS (32.98%) in Ultisols and Spodosols. Although Histosols are naturally high in some nutrients, the use of cover crops still provides benefits, especially pH (0.39), P Bray (79.5 ppm), Exc-K (0.46 meq/100 g), Exc-Mg (0.05 meq/100 g), Exc-Na (0.07 meq/100 g), and BS (0.42%). Overall, *N. biserrata* cover crops demonstrated better results than diverse cover crops, howeverthe importance of selecting the right cover crops to improve soil quality and support the growth of oil palm plants according to soil type should be considered. The Exc-Ca and Exc-Na contents are generally low, highlighting the need for more focused soil management of these nutrients.

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