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Potential agroforestry system on peat land to improve soil chemical properties in Palangkaraya, Central Borneo

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ABSTRACT

Land use management and land cover selection are crucial aspects of the principles of sustainable peatland management. Management of peatlands can significantly impact the lives of local communities and threaten their food security. Therefore, this study aims to compare the characteristics of peatlands based on land management practices in the Klampangan. The chemical properties of the soil under various management practices were evaluated and will be used for multiple considerations in the sustainable utilization of peatlands in the future. This study used a purposive sampling method by composite soil samples from depths of 0–60 cm to analyze the availability and stock of nutrients (i.e., pH H_2O, pH KCl, organic C, total N, available P, exchangeable K, Ca, Mg, and Capacity Exchange Cation (CEC). The nutrient availability data were then processed using an ANOVA analysis and further tested with Duncan's test at a significance level of $p < 0.05$. The results showed that agroforestry land use corn (AJ) and chili (AC) on peatlands is a potential land use for maintaining and providing nutrients. The availability of nutrients did not differ significantly ($p > 0.05$) from monoculture/intensive cropland use. The availability of P was 5.1–5.8 times higher in agroforestry (AJ and AC) compared to DFM land use. The availability of K, Mg, and CEC bases tended to differ significantly ($p < 0.05$) in agroforestry land use, which also affected nutrient stocks. Correlation results showed that organic C played the most significant role ($r = 0.6$) in increasing CEC.

Keywords: agroforestry, Borneo, tropical, peatland, SDGs

INTRODUCTION

Indonesia is one of the countries in the world with a peatlands area and the largest in Southeast Asia (Page et al., 2011). Southeast Asia has 25 million ha of peatlands, which is 60% of all tropical peatlands, and Indonesia has about ± 11.2 Mha to 21 Mha (Wahyunto et al., 2014). After Papua, Central Kalimantan has the second-largest peatland area in Indonesia (± 2.7 Mha) (Hergoualc'h et al., 2018). This extraordinary peatland area can have various impacts, especially in Indonesia and globally, from an ecological, socio-economic, and agricultural perspective. Peatlands serve multiple purposes, including retaining water, providing a home for wildlife unique to the area, and producing commodities for agriculture and forestry (Omar et al., 2020).

Due to their low soil fertility, peatlands are classified as marginal land for agricultural purposes (Ompusunggu et al., 2020). Tropical peatlands are primary carbon, water, and biodiversity reservoirs primarily found along Sumatra's east coast and in Kalimantan's southern and western coastal regions (Taufik et al., 2019). Tropical peat is formed through a paludification process from dead plant biomass. Peat soil differs from mineral soil in that it has a high concentration of organic material, which makes it unique and necessitates careful treatment for agricultural purposes (Agus and Subiksa, 2008). The function of the peat ecosystem may be harmed by the management of peatlands and the choice of commodities that do not align with the characteristics of peatlands (Annisa et al., 2021).

As a country that produces food and raw materials, Indonesia requires large areas of land for farming. Utilizing suboptimal land such as peatlands is one way to boost agricultural output. The peat soil was first cleared to plant coconut or rubber trees. Peatlands were extensively cleared in the 1980s to create room for rice fields, food crops, and the million-hectare rice field project. However, a lack of understanding regarding the characteristics of peatlands and their ecology has led to errors in peatland management in Indonesia (Annisa et al., 2021).

Peatland management in the Central Kalimantan region is experiencing relatively rapid development, with many peatlands being used as agricultural land, as is the case in the Kalampangan region. Peatlands in Borneo are used by the community for rice fields with shifting cultivation systems and rubber (*Hevea brasiliensis*) agroforestry on mineral soils and shallow peat on a small scale (Medrilzam et al., 2017; Jaya et al., 2022) An essential component of the sustainability concept in peatland reclamation and management is managing or regulating land usage and plant selection (Surahman and Shivakoti, 2017). Chemical and physical properties are soil properties that are important to consider in peatland management. Chemical properties such as pH H_2O, N, P, K availability, base saturation and micronutrients are information that needs to be considered when fertilizing peat soil. (Kunarso et al., 2022)Peatland management will significantly impact the lives of local communities whose food security is highly dependent on the natural resources of peatlands (Law et al., 2015). Therefore, peatland use must be managed wisely by considering ecological aspects (Afentina et al., 2021). The primary soil chemical properties used to assess sustainability were pH (in H_2O and KCl solutions), organic carbon (C), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), calcium (Ca), magnesium (Mg) and cation exchange capacity (CEC) (Höyhtyä et al., 2025;). Organic C. pH and CEC were found to be the most indicative of sustainable peatland management, which highlights their importance in retaining nutrients and improving soil fertility (Hikmatullah and Sukarman, 2015; Manalu et al., 2024).

Agroforestry-based land management is essential in the research to bridge management problems in peatlands. Agroforestry is considered a planting system that creates adaptive co-management strategies to maintain the productive function of peatlands (Annisa et al., 2021). Agroforestry is a planting system combining annual crops with annual or food crops, integrating trees on agricultural land and landscapes. The function of agroforestry is to diversify and maintain production to increase social, economic, and environmental benefits for land users. Together, these elements form an integrated approach to land management that promotes more sustainable and environmentally friendly land usage (Noordwijk et al., 2019; Singh et al., 2021).

This research has significant implications for developing sustainable agricultural practices in peat land ecosystems. By investigating the potential of agroforestry to improve soil chemical properties, this study aims to contribute to developing more effective and environmentally friendly agricultural systems. This study is intended to compare the chemical characteristics based on land use in the Kalampangan. Data on the features of chemical properties in various land management are then inventoried and used for multiple considerations on the sustainable use of peat land in the future to minimize the loss of use. The findings of this research will be valuable for policymakers, farmers, and other stakeholders involved in the management of peat land ecosystems, providing insights into the potential benefits and challenges associated with agroforestry systems in these environments.

MATERIAL AND METHODS

Time and place

The research was conducted in Kalampangan, Sebangau, Palangkaraya, and Central Borneo (2°17’34.35”S – 114° 0’47.11”E). The characteristics of peat soil in this area are 0–60 cm deep of peat, while the water depth is > 60 cm. The research used experimental gardening and community gardens in the Kalampangan. The study was carried out in several stages. The first sampling was of six different land uses in Kalampangan, Sebangau, and Central Kalimantan (Figure 1). The second stage is laboratory analysis for soil chemistry in Land Resources Laboratory UPNV "Jawa Timur", and then the analysis of the data that has been obtained continues.

Research design and implementation

This research used a randomized block design (RBD) with different land use management and three replications in each plot. The randomized block design was structured with blocks defined based on land elevation and peat thickness, which are critical factors influencing peatland characteristics. Each block contained plots representing different land-use systems to ensure comparability under similar physical conditions. Soil samples were taken at three depths, i.e., 0–20, 20–40, and 40–60 cm. The treatments in this research are as follows in Table 1.

The research used a survey method to determine soil sampling points. The sampling plot was made, measuring 5 × 5 m. Soil sampling points are taken diagonally. Soil samples were taken compositely using a peat drill 3 times for each land use. Composite soil sampling with three repetitions per land use was employed to ensure representativeness and reduce local anomalies. The results of the composite soil samples were then analyzed at the UPN Surabaya Laboratory to analyze the chemical properties of the soil in the form of pH H_2O, pH KCl, organic C, organic matter, C/N, Total N, availability of P, K exchange, Ca exchange, Mg exchange, Capacity Cation Exchange (CEC) and bulk density (gr/cm^3) each landuse (Dettmann et al., 2022). Measuring the bulk density of peat is crucial for understanding its physical properties and estimating nutrient and carbon stocks. Because peat is a very low-density, high-organic material with high water content, its bulk density is much lower than that of mineral soils, and special care is required in sampling and processing.

Data analysis

The data obtained during the research was compiled using the Microsoft Excel program. Analysis data such as organic C, total N, available P, K exchange, Ca exchange, and Mg exchange are converted into available nutrient stock for each land use with a bulk density reference. The formula used is as follows:

$$Soil\ Nutrient\ Stock\ (g\ m^{-2}) = \frac{Ec\ (g\ kg^{-1}) \times BD(g\ cm^{-3}) \times \Delta D\ (cm) \times 1000\ (cm^2 cm^{-3})}{1000\ (g\ kg^{-1})} \quad (1)$$

Note: *Ec* – soil nutrient concentration, *BD* – bulk density (the value was used from forest area), and ΔD – soil depth. Then, the soil nutrient stocks ($g\ m^{-2}$) were converted to $kg\ ha^{-1}$ or $t\ ha^{-1}$ as a final unit (Allen et al., 2016).

The existing data was then analyzed statistically using Rstudio. Analysis of variance was carried out to determine the effect between treatments. If there is a natural effect at the 5% level, a further Duncan test will be carried out between treatments.

RESULTS AND DISCUSSION

Acidity, organic matter, and macro nutrients in various landuse management

The results of the pH H_2O analysis shown in Table 2, which is included in the actual acidity, show significantly different results ($p < 0.05$) at a 0–20 cm depth in DFM and BL land uses. At a depth of 40–60 cm, the pH of H_2O was significantly different ($p < 0.05$) for all land uses. DFM produces higher H_2O pH values than other land uses, followed by AJ and AC land uses. Meanwhile, potential acidity as pH KCl (Table 2) is

Table 1. History of land

Landuse	Code	History of land management
Dragon fruit monoculture misik	DFM	The Land opened in 2015
Oil palm plantation misik	OPP	The Land opened in 2015
Agroforestry (*Dyera* spp. and Corn)	AJ	The Land opened in 1980
Agroforestry (*Dyera* spp. and Chili)	AC	The Land opened in 1980
Restoration peat	RP	The Land opened in 2016
Forest burnt land	BL	Secondary forest affected by fire in 1997

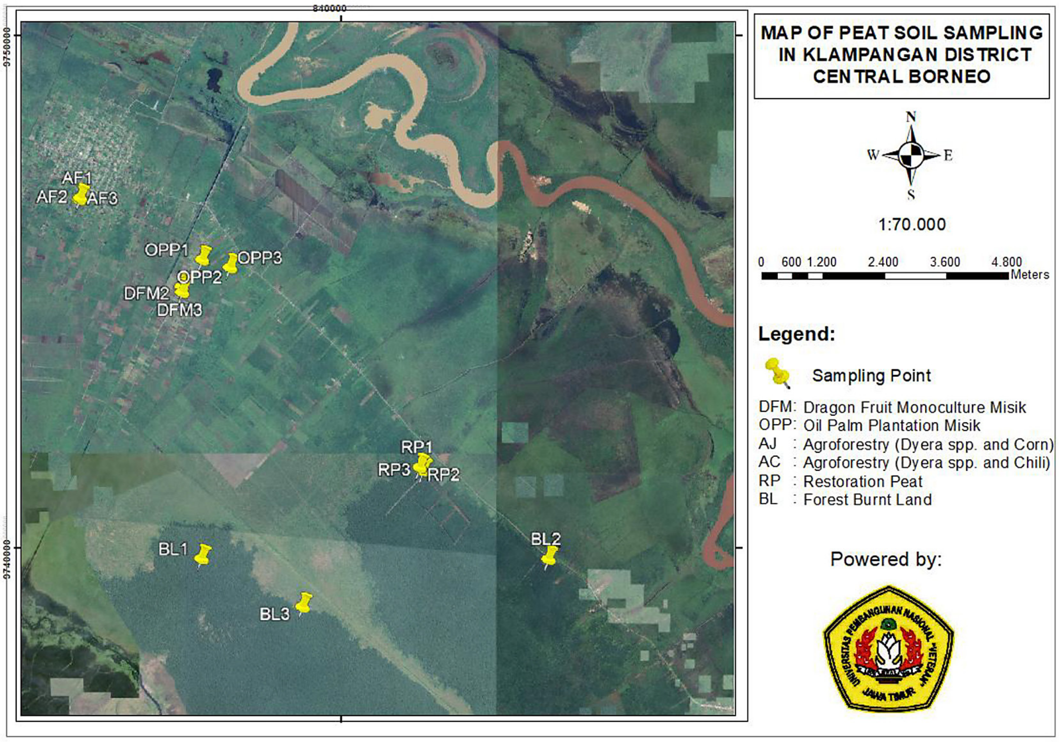

Figure 1. Maps of research site location

significantly different ($p < 0.05$) between land uses AJ, AC, and BL at a depth of 0-20 cm. RP and BL were significantly different at a 20-40 cm depth between OPP and AJ ($p < 0.05$).

Meanwhile, at a depth of 40-60 cm, the pH KCl value was significantly different ($p < 0.05$) in land use between AJ and AC, RP, and BL. In this case, soil acidity is more excellent in intensive land use where fertilizer is applied, likely DFM. Meanwhile, potential acidity is predominantly higher in AJ. This study's analysis of soil chemical properties reveals that the pH H_2O (actual acidity) and pH KCl (potential acidity) across all depths fall within the highly acidic class. The average water pH is higher in the DFM and OPP land use systems.

In contrast, the pH KCl generally resembles the agroforestry system with code AJ and the DFM and OPP monoculture systems (Table 2). The correlation results indicate that adding organic matter or C organic influences the increase in water pH. On the other hand, adding C organic and organic matter does not affect the increase in pH of potassium chloride. This is consistent with the findings of. Jayalath et al (2016) states that adding organic matter and reducing water content in the soil can increase the pH of water in peat soil. The high pH of water in the monoculture systems of DFM and OPP is likely due to the intensive application of lime, which can increase the pH of the soil by binding calcium and magnesium ions that bind to acidic elements such as manganese, iron, and copper, thereby increasing the availability of K, P, and S (Li et al., 2019; Omollo et al., 2016). This is supported by the correlation, which shows that the increase in water pH is accompanied by an increase in calcium and magnesium exchange (Figure 2).

The results of the analysis of organic matter and organic C on various soil depths were significantly different ($p < 0.05$). Soil depth of 0-20 cm, organic C, and organic matter levels are higher in DFM and OPP land uses than other land uses. Meanwhile, at a soil depth of 20–40 cm, the levels of organic C and organic matter were higher in OPP, and at a depth of 40–60 cm, it was higher in DFM compared to RP and BL. AJ and AC land dominated the highest levels of organic C and organic matter use compared to RP and BL. High organic C on intensive land can be caused by slow C decomposition (Batubara and Agus, 2016). This can be seen in intensive fields such as DFM and OPP, which were only opened in 2016. This can be seen in the correlation between water content and organic C, which shows inversely proportional values. The lower the water content,

Table 2. Analysis of acidity and organic matter

Peat landuse management	Soil depth (cm)	pH H_2O	Class*	pH KCl	OC	Class*	SOM
					%		
DFM	0–20	4.2 ± 0.62 a	VA	2.45 ± 0.09 ab	101.68 ± 7.89 a	VH	175.29 ± 13.61 a
OPP		3.9 ± 0.03 ab	VA	2.55 ± 0.03 a	93.08 ± 0.52 a	VH	160.47 ± 0.90 a
AJ		3.5 ± 0.07 bc	VA	2.66 ± 0.25 a	81.05 ± 2.80 ab	VH	139.73 ± 4.82 ab
AC		3.9 ± 0.05 ab	VA	2.70 ± 0.12 a	79.12 ± 24.31 ab	VH	136.40 ± 41.91 ab
RP		3.9 ± 0.11 ab	VA	2.25 ± 0.01 bc	62.72 ± 3.13 bc	VH	108.13 ± 5.40 bc
BL		3.2 ± 0.05 c	VA	2.14 ± 0.06 c	47.53 ± 1.89 c	VH	81.94 ± 3.25 c
DFM	20–40	4.15 ± 0.23 a	VA	2.08 ± 0.07 b	79.61 ± 4.81 b	VH	137.25 ± 8.30 b
OPP		4.23 ± 0.27 a	VA	2.46 ± 0.10 a	121.00 ± 34.02 a	VH	208.61 ± 58.65 a
AJ		3.35 ± 0.02 b	VA	2.09 ± 0.05 b	89.51 ± 12.90 ab	VH	154.32 ± 22.24 ab
AC		3.46 ± 0.16 b	VA	2.29 ± 0.35 ab	77.12 ± 16.34 b	VH	132.96 ± 28.17 b
RP		3.54 ± 0.04 b	VA	2.10 ± 0.01b	53.26 ± 1.39 b	VH	91.83 ± 2.40 b
BL		3.17 ± 0.01 b	VA	2.08 ± 0.03 b	58.71 ± 2.63 b	VH	101.21 ± 4.53 b
DFM	40–60	3.67 ± 0.11 a	VA	2.06 ± 0.04 cd	133.04 ± 31.02 a	VH	229.36 ± 53.48 a
OPP		3.81 ± 0.09 a	VA	2.20 ± 0.12 bc	107.35 ± 19.43 ab	VH	185.06 ± 33.50 ab
AJ		3.47 ± 0.02 b	VA	2.67 ± 0.09 a	78.43 ± 26.97 bc	VH	135.22 ± 46.49 bc
AC		3.28 ± 0.03 c	VA	2.25 ± 0.10 b	95.25 ± 14.12 abc	VH	164.21 ± 24.35 abc
RP		3.32 ± 0.04 c	VA	2.01 ± 0.01 d	53.83 ± 2.03 c	VH	92.80 ± 3.49 c
BL		3.10 ± 0.04 d	VA	1.99 ± 0.07 d	55.58 ± 3.78 c	VH	95.82 ± 6.51 c

Note: Numbers accompanied by the same letter in the column indicate no significant differences in the 5% Tukey test. VA: very acidic; VH: very high, *(Badan Standarisasi Instrumen Pertanian, 2023).

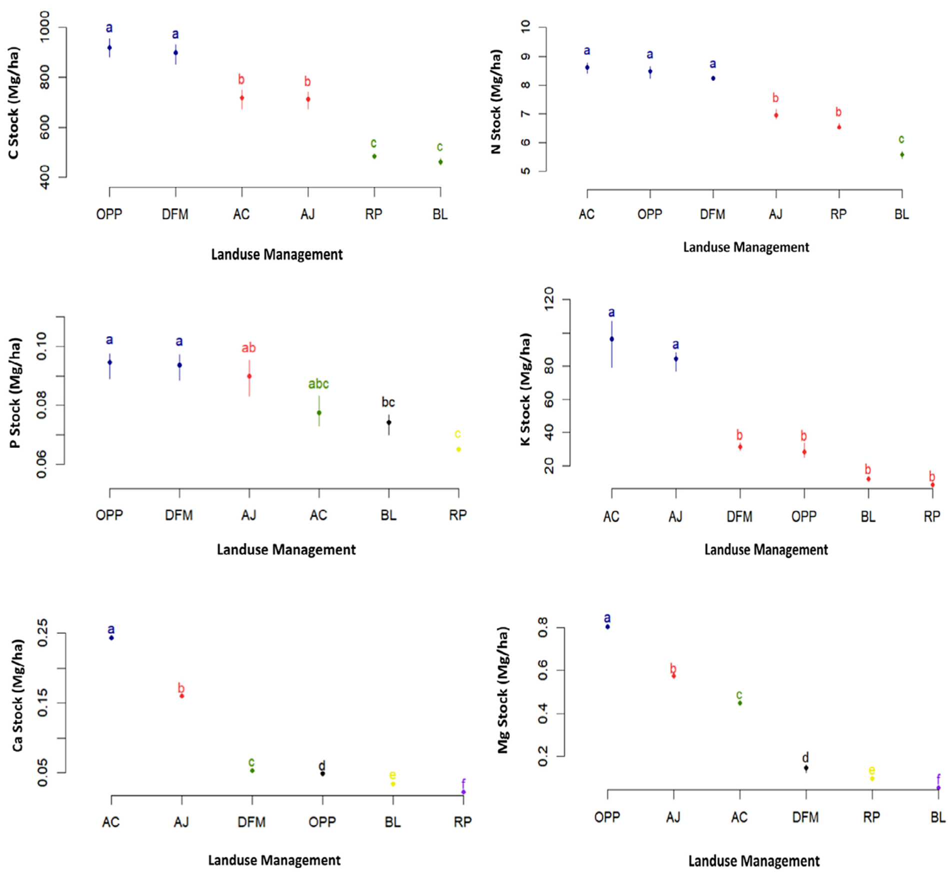

Figure 2. Nutrients stocked in various land use management. Numbers accompanied by the same letter in the column indicate no significant differences in the 5% Tukey test

the higher the availability of C (Figure 2). Composting theory states that the relationship between water content and the availability of organic C is inversely proportional, where an increase in water content is not followed by an increase in organic C (Ratna et al., 2017).

Macronutrients prime in various landuse management

The total N availability for each land use is shown in Table 2. The total N availability at a depth of 0–20 cm is significantly different ($p < 0.05$), where the DFM and OPP land uses have higher total N than other land uses. At depths of 20–40 cm and 40–60 cm, total N was significantly different ($p < 0.05$) in AC land use. Total N levels were higher than in the other five types of land use. The availability of P in peatlands in various land uses is presented in Table 3. At a 0–60 cm depth, DFM land with AJ and AC is not significantly different compared to OPP, LR, and BL land uses.

The classification categories (e.g., "very high," "moderate") were based on national soil fertility standards established by the Indonesian Agency for Agricultural Research and Development (IAARD) (Badan Standarisasi Instrumen Pertanian, 2023). These thresholds are commonly used in local agronomic assessments and were selected for their regional relevance.Total N availability is classified as high to very high (Table 3). The average total N was higher in the topsoil in DFM and OPP land uses, while at depths of 20–40 cm and 40–60 cm, the highest total N values were dominated by AC land uses. Where AC land use total N values are 1–1.3 times higher than OPP and DFM (Table 2). The easily mobile nature of N is thought to be the cause of the low total N in the subsoil depth compared to the topsoil. The study suggests that the type of land use affects the availability and loss of nutrients in peat soil. Similar findings were reported by Fitria et al. (2021) and Kurniawan et al. (2021), which explained that land use and vegetation type affect the availability of soil nutrients. The monoculture systems of DFM and OPP, which are intensive land use systems, show higher macro-nutrient availability, such as N, in the topsoil than in the subsoil. The fertilization effect likely contributed to the high N levels in the topsoil of DFM and OPP.

The availability of the macronutrient P is included in the very high (Table 3). The availability of P at a depth of 0–20 cm tends to be higher

Table 3. Analysis of macronutrient prime

Peat land management	Soil depth (cm)	TN	Class*	AP	Class*
		%		ppm	
DFM	0–20	1.03 ± 0.05 a	VH	74.95 ± 15.46 a	VH
OPP		1.03 ± 0.04 a	VH	44.43 ± 11.49 b	VH
AJ		0.80 ± 0.04 bc	VH	438.50 ± 132.62 a	VH
AC		0.63 ± 0.04 c	H	388.71 ± 76.71 a	VH
RP		0.90 ± 0.14 ab	VH	31.73 ± 8.52 b	VH
BL		0.65 ± 0.07 c	H	61.93 ± 8.63 b	VH
DFM	20–40	0.91 ± 0.05 c	VH	103.05 ± 16.78 ab	VH
OPP		1.05 ± 0.09 b	VH	102.37 ± 43.09 ab	VH
AJ		0.72 ± 0.01 d	VH	140.73 ± 28.46 ab	VH
AC		1.18 ± 0.03 a	VH	271.21 ± 226.43 a	VH
RP		0.65 ± 0.04 d	H	27.11 ± 3.88 b	VH
BL		0.73 ± 0.06 d	H	34.08 ± 5.01 b	VH
DFM	40–60	0.94 ± 0.01 b	VH	103.62 ± 10.08 b	VH
OPP		0.86 ± 0.06 bc	VH	104.78 ± 15.98 b	VH
AJ		0.91 ± 0.06 bc	VH	176.97 ± 34.02 a	VH
AC		1.20 ± 0.10 a	VH	202.60 ± 50.92 a	VH
RP		0.73 ± 0.08 cd	H	15.87 ± 2.30 c	VH
BL		0.57 ± 0.16 d	H	12.89 ± 4.23 c	H

Note: Numbers accompanied by the same letter in the column indicate no significant differences in the 5% Tukey test. VL: Very low; L: low; M: Moderate; H: High; VH: Very High *(Badan Standarisasi Instrumen Pertanian, 2023).

in DFM land use. However, at a depth of 20–40 cm, it was higher in AJ and AC land use than in DFM monoculture land use. The AJ and AC produce available P values 5.1–5.8 times higher than DFM. Likewise, at a 40–60 cm depth, AJ and AC land uses have 1–1.82 times higher P availability than DFM, and OPP land uses are 11–13 times higher than RP and BL land uses. In the management of agroforestry (AJ and AC) and monoculture land (DFM and OPP), inorganic fertilizer is applied to increase nutritional input. It is suspected that intensive land management in DFM and OPP causes the topsoil layer to produce higher total N and available P than AJ and AC.

Meanwhile, at subsoil depth the value is lower than AJ and AC. The higher mobility of N due to leaching caused by high rainfall in tropical regions, particularly in NO3- in peat soil, is likely to have affected the higher P levels (Azis et al., 2022; Maftu'ah et al., 2014). The type of land use affects the loss of nutrients in intensive systems through evaporation or leaching (Fitria et al., 2021). The low P levels in the DFM and OPP systems are likely due to shorter plant roots. In contrast, the agroforestry system with *Dyera* spp. can act as a nutrient trap, reducing vertical and horizontal nutrient leaching (Suryani and Dariah, 2012). The closed nutrient cycle in agroforestry systems can maintain nutrients within the soil system, as tree roots can recycle nutrients from organic fertilizers used by plants, thereby increasing fertilization efficiency (Sileshi, 2020).

Base cation in various landuse management

The availability of bases such as K and Mg cation exchange is significantly different ($p < 0.05$) at a 0–20 cm depth where AJ land is used. Meanwhile, at the same depth, magnesium and CEC were significantly different ($p < 0.05$), higher in AC land use compared to other land uses. At a depth of 20–40 cm, the exchangeable K value is significantly different for AC land use compared to other land uses. Meanwhile, the Ca base is significantly different in OPP land use compared to other land uses. Mg base is significantly different ($p < 0.05$) in AJ land use. AJ and AC agroforestry land produces higher Mg availability than other land uses throughout the peat soil depth. The CEC value is significantly different ($p < 0.05$) in the AJ (agroforestry type land use) at a depth of 0–20 cm. This value is higher compared to other land uses.

Meanwhile, at a depth of 20–40 cm, CEC is significantly different ($p < 0.05$) in OPP land use, where the CEC value is higher in this land use. Meanwhile, codes AJ and AC produce the second-highest CEC after OPP. AJ is significantly different at a 40-60 cm depth ($p < 0.05$), where this land use produces higher CEC than other land uses. It is suspected that the pH of KCl is positively correlated with the availability of exchangeable nutrients such as K, Ca, and Mg, although not so strongly (Figure 2) as in research conducted by Wang et al. (2019) which explains that pH H_2O and pH KCl are positively correlated with the availability of bases.

The base cations such as K, Ca, Mg, and KTK in Table 4 show that the average levels are higher in the agroforestry systems (AJ and AC). K, Ca, and Mg exchangeability is higher in the agroforestry systems (AJ and AC). At the same time, the stock availability of Mg is higher in the OPP system due to the additional application of Mg as a fertilizer in oil palm. The CEC levels in the agroforestry systems (AJ and AC) are similar to those in intensive systems (OPP and DFM). In contrast, the CEC levels in the RP and BL systems are lower, likely due to the lack of fertilization and higher base leaching caused by less vegetation(Liu et al., 2018). The high levels of C organic in peat soil affect CEC in the soil (Figure 2), consistent with the findings by (Bi et al., 2023; Hikmatullah and Sukarman, 2015).

Nutrition stock in various landuse

Nutrient stocks in various land uses are shown in Figure 1. The analysis and calculation results of nutrient stocks in peatlands show significant differences ($p < 0.05$) across all land uses. C stock is significantly different ($p < 0.05$) between land uses DFM, OPP, AJ, AC with RP and BL. Meanwhile, the C stock value on monoculture land uses such as DFM and OPP is not significantly different ($p > 0.05$) from agroforestry land (AJ and AC). The availability of C stock is related to the level of organic matter and C (%), and a high C stock indicates that the decomposition process of organic matter is prolonged (Batubara and Agus, 2016). The slow decomposition process will be related to the supply of nutrients to the soil. After organic material undergoes decomposition by microorganisms, organic material can be used as a source of complex nutrients (Fontaine et al., 2003). This can be seen in the

Table 4. Analysis of base cation exchange

Peat land management	Soil depth (cm)	K	Class*	Ca	Class*	Mg	Class*	CEC	Class*
		Cmol/kg		Cmol/kg		Cmol/kg		Cmol/kg	
DFM	0–20	0.29 ± 0.01 d	L	2.66 ± 0.02 c	L	4.20 ± 0.01 c	H	256.10 ± 6.68 ab	VH
OPP		0.26 ± 0.01 e	L	1.34 ± 0.01 d	VL	3.68 ± 0.01 d	H	277.89 ± 6.25 a	VH
AJ		1.36 ± 0.01 b	VH	7.15 ± 0.01 b	M	4.93 ± 0.01 a	H	272.87 ± 27.29 a	VH
AC		2.07 ± 0.01 a	VH	9.32 ± 0.01 a	M	4.81 ± 0.00 b	H	238.70 ± 4.43 b	VH
RP		0.11 ± 0.01 f	L	0.63 ± 0.01 f	VL	1.82 ± 0.01 e	M	131.84 ± 5.81 c	VH
BL		0.33 ± 0.01 c	L	0.71 ± 0.00 e	VL	1.67 ± 0.01 f	M	117.09 ± 14.77 c	VH
DFM	20–40	0.37 ± 0.01 c	M	0.78 ± 0.01 e	VL	4.33 ± 0.001 c	H	266.54 ± 14.33 b	VH
OPP		0,38 ± 0.01 c	M	11.90 ± 0.01 a	H	2.98 ± 0.01 d	H	325.63 ± 30.29 a	VH
AJ		0.73 ± 0.01 b	H	3.42 ± 0.01 b	L	4.80 ± 0.01 a	H	245.14 ± 8.00 b	VH
AC		1.02 ± 0.01 a	VH	1.37 ± 0.01 c	VL	4.49 ± 0.01 b	H	227.73 ± 26.95 b	VH
RP		0.13 ± 0.01 e	L	1.00 ± 0.01 d	VL	2.91 ± 0.001 e	H	130.15 ± 24.73 c	VH
BL		0.21 ± 0.01 d	L	0.47 ± 0.01 f	VL	1.23 ± 0.01 f	M	131.39 ± 1.30 c	VH
DFM	40–60	0.28 ± 0.01 c	L	0.89 ± 0.95 d	VL	3.67 ± 0.01 c	H	252.77 ± 2.22 b	VH
OPP		0.22 ± 0.00 d	L	10.23 ± 0.01 a	M	2.69 ± 0.01 d	H	290.08 ± 10.73 ab	VH
AJ		0.71 ± 0.01 b	H	6.18 ± 0.00 b	M	5.31 ± 0.01 a	H	331.09 ± 19.74 a	VH
AC		1.17 ± 0.01 a	VH	2.39 ± 0.01 c	L	4.39 ± 0.01 b	H	210.19 ± 15.27 c	VH
RP		0.16 ± 0.01 e	L	1.16 ± 0.01 d	VL	2.37 ± 0.00 e	H	128.22 ± 7.52 d	VH
BL		0.07 ± 0.01 f	VL	0.45 ± 0.01 d	VL	0.60 ± 0.00 f	L	154.23 ± 37.47 d	VH

Note: Numbers accompanied by the same letter in the column indicate no significant differences in the 5% Tukey test. VL: Very low; L: low; M: Moderate; H: High; VH: Very High *(Badan Standarisasi Instrumen Pertanian, 2023).

higher C stock on OPP and DFM land. A high soil C stock can indicate that C uptake is high, but this cannot suggest negligible emissions (Selvia et al., 2023). This requires C stock data on the soil and calculates the base area of the tree and tree density (Fitria and Kurniawan, 2023).

The N stock was not significantly different ($p > 0.05$) in land use between OPP and AC, while between AC and BL it was significantly different ($p < 0.05$). The value of N stock is similar to C stock, although AC has a higher value than other land uses. It was related to the availability of soil C stock. This can be seen in the correlation results between organic C and total N, which is directly proportional although insignificant (Figure 2). However, according to (Marty et al., 2017; Zhang et al., 2021), total N in the soil was contributed by 7–19% of organic material originating from plant waste and residue such as leaves and stems. This plant litter is then broken down through biochemical cycles or decomposition into various nutrients, including total N (Marty et al., 2017).

P stock is significantly different ($p < 0.05$) in OPP and RP, whereas DFM, AC, AJ, and BL have similar P stock in land uses. There is no significant difference between intensive land and agroforestry. This could be due to fertilizer application for annual plants with high levels of available P, especially in the topsoil (Anda and Dahlgren, 2020). So, it affects the P stock in peat. In addition, organic material that has undergone weathering on DFM, AC, AJ, and BL land produces higher P availability than on RP land that has just been restored (Mabagala, 2022). K stock is significantly different ($p < 0.05$) in land use AJ and AC compared with other land uses; it is suspected that peat in tropical areas washes a lot of bases such as K (Krug and Frink, 1983; Wang et al., 2019). So, the availability of K stock is higher on agroforestry land (AJ and AC). It is known that tree roots in agroforestry land can become a net for capturing leached nutrients (Sileshi, 2020).

Ca Stock significantly differs ($p < 0.05$) in land use between AC and, DFM and OPP monoculture land use. Ca stock in agroforestry land use (AJ and AC) is higher than other land uses. Mg Stock is significantly different ($p < 0.05$) in OPP land use compared to other land uses. Meanwhile, AJ and AC have the second highest land use after that. The nutrient stock values in this study show that BR and RP have lower fertility levels. Research conducted by Arsanty et al. (2020) and

Vasyl et al. (2020) stated that burning peatlands results in loss of soil fertility. Other research states that burning peatlands causes a decrease in total N by 6%, CEC by 8%, and soil organic C by 2% (Suryani et al., 2022). Although peatland restoration (RP) aims to restore soil health and restore microbiological biodiversity, it takes decades and requires regular monitoring (Bhomia and Murdiyaso, 2021; Sakuntaladewi et al., 2022).

Correlation of parameters

Correlation between parameters is carried out to determine the strength of influence between one parameter and other parameters. The correlation analysis in this study is presented in Figure 3. The correlation between organic C and organic matter and CEC is shown ($r > 0.6$), which shows that adding organic material increases the availability of CEC in the soil. Meanwhile, increasing the availability of P influences the increase in K exchange and Mg exchange ($r > 0.6$) – likewise, growing bases such as Ca exchange and Mg exchange increase CEC. The high pH of KCl (potential of acidity) affects the availability of P, which is directly proportional to the pH of KCl.

The differences in land use in peat soil management are crucial because they are related to the stock of nutrients and soil fertility, which affect management (Annisa et al., 2021; Hermanns et al., 2017). The stock of nutrients such as C, N, and P between intensive and agroforestry systems shows similarities, while the peat soil rehabilitation system tends to have lower nutrient reserves. This is likely due to the different levels of peat maturity and land management, such as fertilization practices. Adding inorganic fertilizers combined with organic matter increases the availability of nutrients in the soil, mainly by applying fertilizers containing quick-release minerals that provide N and P (Uddin et al., 2023; Fitra et al., 2019). The agroforestry system in this study is a potential land use system for peat soil. The agroforestry system can store nutrients better than intensive and rehabilitation systems. This is consistent with the findings of (2017), which state that non-woody plants have a high risk of nutrient leaching, erosion, and runoff.

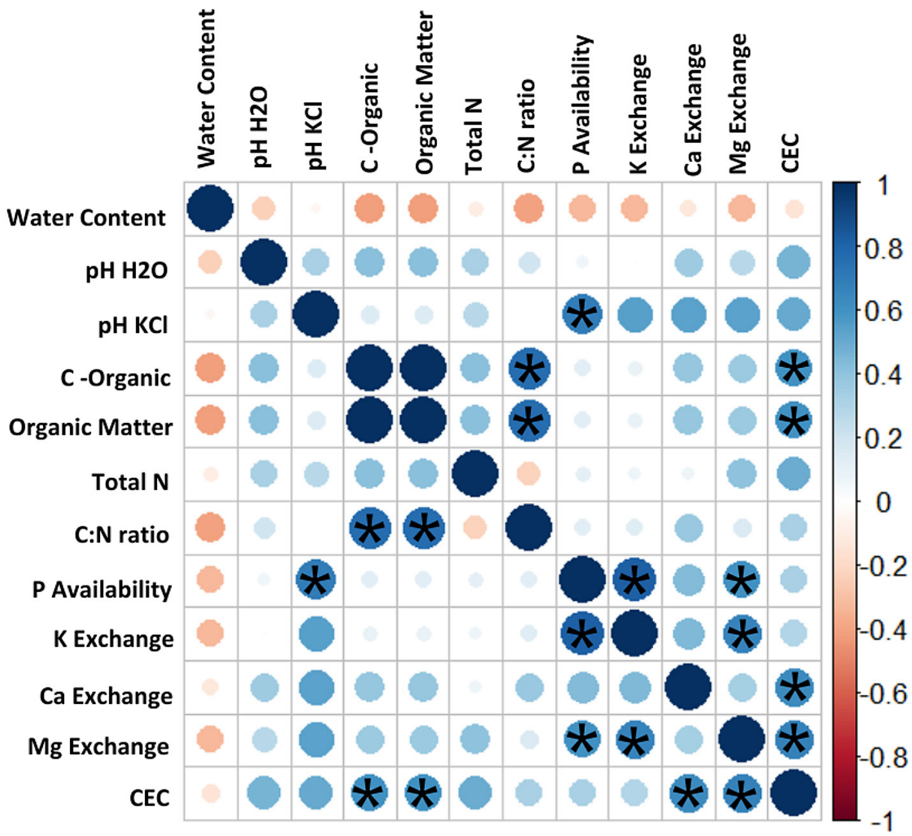

Figure 3. Correlation between parameters of soil chemical. A darker blue color indicates a more substantial correlation number with a positive value. Meanwhile, a darker red color indicates a stronger but negative correlation. The sign (*) indicates the significance of the parameter

CONCLUSIONS

The study on soil chemical properties reveals that the pH levels of water and potassium chloride in peat soils are highly acidic across various depths, with higher water pH levels in the DFM and OPP land use systems due to lime application. The higher soil pH observed may be attributed to lime application, which not only neutralizes soil acidity but also improves nutrient availability especially calcium and magnesium. The addition of organic matter influences water pH but not potassium chloride pH. Land use significantly affects nutrient availability and loss in peat soils. Intensive systems like DFM and OPP show higher nitrogen levels in topsoil due to fertilization. In contrast, agroforestry systems, such as AJ and AC, exhibit better nutrient retention and reduced leaching, attributed to deeper root systems and closed nutrient cycles. Base cation levels are higher in agroforestry systems, enhancing soil fertility and nutrient stock. It demonstrates that land use plays a critical role in influencing the chemical properties of peat soil in Central Kalimantan

Therefore, agroforestry can be considered a promising land management strategy for sustaining and gradually enhancing nutrient retention in tropical peatlands, provided it is integrated with appropriate fertilization and long-term management practices. These findings support the inclusion of agroforestry in sustainable peatland development plans, though site-specific conditions and nutrient dynamics should be carefully monitored. The study underscores the importance of land use in peat soil management, highlighting agroforestry systems' potential to maintain soil nutrients more effectively than intensive or rehabilitation systems. The findings align with previous research, emphasizing the benefits of combining organic and inorganic fertilization for nutrient availability and soil fertility.

These findings reinforce the study's objectives and demonstrate that agroforestry is a promising strategy for sustainable peatland management. This approach supports multiple Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger) by improving soil fertility for food production, SDG 13 (Climate Action) through carbon retention in peat soils, and SDG 15 (Life on Land) by promoting sustainable use of terrestrial ecosystems. Integrating agroforestry into land use planning in peatland regions offers a pathway toward environmentally sound and socially inclusive agricultural development.

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