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## Analysis of peat soil physical properties under different land uses in Seluma Regency, South Sumatera

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**Abstract** The results showed that rubber plantations had the lowest bulk density (0.35 ton/m<sup>3</sup>) and the highest permeability (87.87 cm/hour), while paddy fields had the highest bulk density (0.66 ton/m<sup>3</sup>) and the lowest permeability (5.87 cm/hour). The highest total pore space was found in rubber plantations (74.56%), whereas paddy fields had the lowest pore space in the subsoil (56.02%). Water content was highest in the subsoil of rubber plantations (38.46%) and lowest in shrubland (22.22%). The highest organic C-content was observed in rubber plantations (33.68%), while the lowest was in paddy fields (9.6%). Oil palm plantations and paddy fields had more mature peat (sapric), whereas rubber plantations and shrubland maintained more natural peat conditions. Analysis using Partial Least Squares Structural Equation Modeling, demonstrated that land use significantly affects peat soil's physical properties, particularly bulk density, total pore space, permeability, and water content. Land conversion influences peat subsidence and decomposition, highlighting the need for sustainable management to prevent land degradation and maintain ecosystem balance.

**Keywords:** Land conversion, Organic content, Permeability, Water content

### Introduction

Indonesia is one tropis country that have a peat soil of 21 million hectares in Sumatra, Kalimantan dan Papua (Yuliana *et al.*, 2022). Unlike the soil in general, peat soil has unique physical characteristics influenced by land use, about 35% of Sumatra, 32% of Kalimantan, 30% of Papua and 3% the other terricore (Maysarah *et al.*, 2021). Peaty soil has a vital utility in of carbon, hydrologi and biological diversity. Peatlands are unique ecosystems for med through the accumulation of organic matter over thousands of years these ecosystems play a vital role in carbon storage, hydrological regulation, and supporting biodiversity. According to Annisa and Nursyamsi (2017) tropical peatlands store a significant amount of carbon and are highly vulnerable to

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climate change and human activities, making them a crucial component in the mitigation of global climate change.

In Bengkulu Province, particularly in Sukaraja Subdistrict, Seluma Regency, peatlands are under significant pressure due to land-use conversion. The peatland areas in this region have been transformed into various types of land use, including Rubber plantations, Oil palm plantations, Paddy fields, and Shrublands. The conversion has led to substantial changes in the physical characteristics of peat soils, which can affect their ecological functions (Nusantara *et al.*, 2012). The conversion of peat forest areas for agricultural and plantation activities poses a threat to the sustainability of peatland ecosystems and may result in adverse environmental consequences. The degradation of peat forests impacts the environment through the release of soil carbon (C) and the emission of C into the atmosphere (Syaputri, 2021).

The conversion of peatlands for agricultural purposes often becomes a point of contention due to the environmental impacts it causes. The transformation of peat forests and the construction of drainage systems can lead to an increased risk of forest fires as a result of carbon stock release. According to a study by Arisanty *et al.* (2020) Indonesia ranks as the third-highest country in terms of air pollution caused by forest fires over the past decade. Seluma Regency is also identified as one of the regions with a high risk of forest fires (Daly *et al.*, 2015). The issues arising from peatland conversion in Sukaraja Subdistrict include soil quality degradation, fire risk, and greenhouse gas emissions. A study conducted by Irma *et al.* (2018) identified that the conversion of peatlands into plantations—such as Oil palm and Rubber in Sumatra can increase CO<sub>2</sub> emissions by up to 20-25 tons per hectare per year, negatively impacting environmental quality and the resilience of peatland ecosystems.

Although the impacts of peatland conversion have been widely studied, there remains a gap in understanding the specific relationships between different types of land use and changes in the physical properties of peat soils, particularly at the local level. Comprehensive research analyzing variations in physical soil properties across various land uses and depths is still limited in Sukaraja Subdistrict. This study is important to address that gap by analyzing the physical characteristics of peat soils under different land uses (Rubber plantations, Oil palm plantations, Paddy fields, and Shrublands) and at different depths (topsoil and subsoil). The application of the PLS-SEM method in the analysis will enable a deeper understanding of the causal relationships between land use and changes in physical soil properties (Tenaya dan Utami, 2015).

Unlike the soil in general, peat soil has unique physical characteristics influenced by land use. This study aimed to the physical properties of the peat

soil in Seluma Regency, South Sumatera. The studied land use included rubber plantations, oil palm plantations, paddy fields and shrubland.

## **Materials and methods**

The main survey was done by soil sampling for laboratory analysis as part of the core research activities. The sampling locations covered four different types of land use, namely Rubber plantations, Oil palm plantations, Paddy field areas, and Shrubland areas. In each land use type, samples are taken from three different locations with an interval distance of approximately 10 meters between sampling points. At each sampling point, samples are collected at two different depth levels: the topsoil layer (0–20 cm) and the subsoil layer (20–40 cm). This process is carried out to ensure a comprehensive representation of soil/peat conditions at the research sites. For each type of land use, a total of 12 undisturbed soil samples and 6 disturbed soil samples are collected, resulting in 72 soil samples obtained from the four types of peatland use.

The materials used in this study were administrative maps with a scale of 1:125.000, sample point maps obtained from the overlay of land use maps and soil type maps with a scale of 1:55.000 taken from Citra SAS Planet and RBI (Rupa Bumi Indonesia), as well as laboratory materials intended for the analysis of soil physical properties. The study used a descriptive method to identify and compared the physical properties of peat soil in several different land uses. The collected data were analyzed in the Soil Science Laboratory to obtain qualitative results of the soil's physical properties, then the data obtained will be processed using the Partial Least Squares Structural Equation Modeling (PLS-SEM) method using Warp PLS 7.0 software. To determine how exogenous/dependent latent variables (physical properties of soil) are influenced by exogenous/independent latent variables (land use), or how endogenous latent variables can influence other endogenous variables using a model. The steps for analysis using PLS-based SEM were as follows: validity and reliability testing of instruments (confirmatory factor analysis), testing of models between variables (path analysis) and obtaining a suitable model for prediction (structural model analysis and regression analysis).

Before conducting field research, the preparation stage included a literature review aimed at collecting books, journals, and articles related to the research topic, as well as gathering information about the study area. The next step was to plan the sampling technique, determined the required number of samples, the sampling method, and the treatment of samples after collection. Subsequently, a research location map is based on the overlay results of the administrative map, land use map, and soil type map. The pre-survey stage is carried out prior to the

survey implementation with observing field conditions, ensuring the suitability of land use at the predetermined research location, determining sampling points, and managing the permits for sample collection sites.

The method for collecting disturbed soil samples involved the use of a soil auger, with approximately 1 kg of soil taken from each sampling point and depth. Each sample is then labeled. For the collection of undisturbed soil samples, the used tools included a sample ring, a field knife, and sample containers. At the designated location, the sample ring is placed on the soil surface and gently pressed until it is fully inserted into the soil without disturbing the soil structure. Afterward, the soil surrounding the ring is carefully cut before being lifted. The sample is then cleaned, sealed to prevent moisture loss, labeled, and stored for laboratory analysis. The collected variables in the field are presented in the Table 1 demonstrated bulk density, porosity, moisture content, permeability, Walkley and Black method, Peat Maturity (Squeeze Method) and Peat Thickness. Soil permeability describes the ability of soil to transmit water (Pratama *et al.*, 2017) and (Hamdani, 2020). The studied land uses included rubber plantations, oil palm plantations, paddy fields, and shrubland. The analyzed variables included bulk density, total pore space, water content, permeability, organic C-content, peat maturity, and thickness.

## Results

Bulk density can indicate the level of soil compaction, where a higher bulk density value signifies a higher degree of soil compaction. Each land use type showed a different soil bulk density (Table1).

**Table 1.** Soil bulk density ad porosity

Land use	Depth (cm)	BV (ton/m <sup>3</sup> )	Porosity (%)
Rubber	0-20	0.35	74.56
	20-40	0.42	70.07
Oil palm	0-20	0.49	64.53
	20-40	0.52	62.73
Paddy field	0-20	0.44	68.42
	20-40	0.66	56.02
Shrubland	0-20	0.36	74.10
	20-40	0.51	63.32

Water content was the highest in the subsoil of rubber plantations (38.46%) and lowest in shrubland (22.22%) as based on Table 2. It declined that seem to be the most likely which caused by natural soil compaction due to the pressure

exerted by the overlying soil layers, which contributed to the reduction in porosity at greater depths.

**Table 2.** Soil moisture content, permeability and organic carbon

Land use	Depth (cm)	Moisture Content(%)	Permeability (cm/hr)	Organic Carbon (%)
Rubber	0-20	23.48	87.87	33.68
	20-40	38.46	68.17	45.55
Oil palm	0-20	28.18	17.53	14.32
	20-40	30.55	16.04	15.06
Paddy field	0-20	27.68	17.18	15.06
	20-40	37.86	5.87	10.49
Shrubland	0-20	22.22	11.84	30.75
	20-40	25.43	10.23	20.71

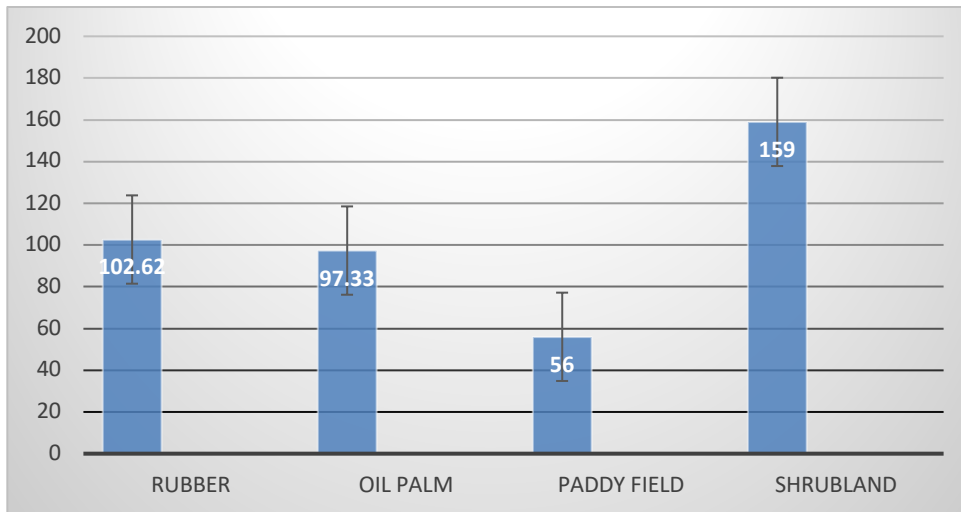
Peat maturity information across various land uses in Sukaraja District is presented in Table 3. The data were obtained through direct field observations using the Von Post method showing different depth and criteria.

**Table 3.** Peat maturity under various peatland land uses

Land use	Depth	Criteria	Description
Rubber	0-20 cm	Hemic	Remaining fiber content of less than 3/4 portion
	20-40 cm	Sapric	Remaining fiber content of less than 1/4 portion
Oil palm	0-20 cm	Sapric	Remaining fiber content of less than 1/4 portion
	20-40 cm	Sapric	Remaining fiber content of less than 1/4 portion
Paddy field	0-20 cm	Sapric	Remaining fiber content of less than 1/4 portion
	20-40 cm	Sapric	Remaining fiber content of less than 1/4 portion
Shrubland	0-20 cm	Sapric	Remaining fiber content of less than 1/4 portion
	20-40 cm	Sapric	Remaining fiber content of less than 1/4 portion

\*Source: Hamdani (2020)

Peat depth plays a significant role in influencing soil bearing capacity. Greater peat depth is often associated with higher fiber content and softer texture, especially in immature peat. This condition is made the soil less stable and more difficult to support the planted crops. Rubber trees, as plantation crops that required good soil stability for their root systems which affected by this condition, which is indicated by leaning rubber trees on peatlands (Figure 1).



**Figure 1.** Peat thickness under various peatland uses

## Discussion

The research is geographically located around  $-3.96^{\circ}$  LS and  $102.38^{\circ}$  BT in the Sukaraja Subdistrict, Seluma Regency the sampling area is approximately 25 km from the center of Bengkulu City. Sukaraja Subdistrict is situated to the west of Tais, the capital of Seluma Regency. The total area of Sukaraja Subdistrict is approximately 18.945,78 hectares, with peatland covering around 4.151 hectares. Subdistrict Seluma Regency, is located in Bengkulu Province and is bordered by Central Bengkulu Regency to the north, Air Periukan Subdistrict to the south, Lubuk Sandi Subdistrict to the east, and directly adjacent to two regions on the west side: Bengkulu City and the Indian Ocean (BPS Seluma, 2023).

The results of bulk density (BD) measurements under various peatland use types showed that the rubber land use had the lowest BD in the topsoil layer (0–20 cm), which was  $0.35 \text{ ton/m}^3$ . The low BD value is influenced by several factors, including the high accumulation of litter from falling rubber leaves, as well as minimal mechanical disturbance on the soil surface due to the absence of intensive soil cultivation. Based on the findings of the study, Iskandar (2014) indicated that the high accumulation of litter and protection from the canopy can minimize soil compaction, thereby resulting in lower soil bulk density. On the other hand, the paddy field land use showed the highest BD value in the subsoil layer (20–40 cm), amounting to  $0.66 \text{ ton/m}^3$ . This condition occurred as a result of several factors related to the intensive management practices of paddy field land use. According to Susilawati and Fahmi (2013) who stated that periodic

flooding in paddy field areas led to natural soil compaction through the process of eluviation. Karimah *et al.* (2020) explained that the repeated mechanical soil tillage in paddy field areas can lead to the formation of a compact plow pan layer. The continuous pressure is exerted by the standing water during flooding also contributed to the high BD value in this layer (Susilawati and Fahmi, 2013).

Soil porosity is one of the important indicators in determining soil fertility and its capacity to support plant growth. Based on the data, all types of land use decreased in porosity with increasing depth. This decline is most likely caused by natural soil compaction due to the pressure exerted by the overlying soil layers, which also contributed to the reduction in porosity at greater depths (Junaidi *et al.*, 2021). In addition, lower biological activity-such as root movement and soil organism activity-in the deeper layers are limited the formation of natural pore spaces. The lower organic matter content at this depth led to the deterioration of soil structure and reduced the soil's capacity to retain water and air. The physical characteristics of peat soil generally exhibited high soil porosity, which led to low bulk density and a loose soil structure. Changes in land use resulted in alterations to soil structure, thereby affecting the physical condition of peat soil, with variations in soil porosity and bulk density. In general, peat soil porosity was very high, ranging from 86% to 91% (Najiyati *et al.*, 2005). However, its quality may decline under conditions of intensive soil management. Intensive land cultivation, such as the repeated plowing and the use of chemical fertilizers without being balanced by organic fertilizers, can lead to soil compaction. Moreover, excessive canal construction and drainage regulation can cause peat soil to shrink, dry out, and become prone to fire, thereby accelerating the decomposition process and resulting in subsidence.

In addition, lower biological activity-such as root movement and soil organism activity-in the deeper layers are limited the formation of natural pore spaces. The lower organic matter content at this depth led to the deterioration of soil structure and reduced the soil's capacity to retain water and air. Different types of land use result in variations in evapotranspiration, infiltration, and water distribution within the soil profile, which ultimately affect the moisture content at various soil depths. The highest soil moisture content was found in the rubber land use at a depth of 20–40 cm, with a value of 38.46%, while the lowest soil moisture content was found in the Shrubland at the same depth, which was 22.22%.

At the 0–20 cm depth, the land use with the highest moisture content was the paddy field (27.68%), whereas the land use with the lowest moisture content was the rubber plantation (23.48%). Based on the research findings, the moisture content in peatland areas in this region was recorded at approximately 30%, with

some areas even showing moisture levels around 20%. Naturally, peat soil showed a high capacity to retain water due to its loosely structured organic fibers. The water retention capacity of peat soil was extremely high which indicated by its ability to hold water up to 13 times its dry weight, with a range from 100% to 1.300% (Ratmini, 2012). However, the moisture content was lower than that range which may be influenced by various factors.

Soil permeability is the soil's capacity to transmit water when it is saturated condition (Rahmawati Putri *et al.*, 2023). The highest soil permeability was found in rubber land at a depth of 0–20 cm, recorded at 87,87 cm/hour. Rubber trees tended to produce a large amount of litter, which decomposed and increased the organic matter content on the soil surface. This is enhanced soil looseness and contributed to the formation of soil pores, thereby improving the soil's ability to absorb and transmit water (Jakarius *et al.*, 2021). However, at a depth of 20–40 cm, there was slightly decreased in permeability to 68,17 cm/hour. This decline is attributed to the subsoil's denser structure and smaller soil pores compared to the topsoil, resulting in lower permeability. Biological activity in the subsoil is also contributed to the soil's ability to retain water for a longer period (Triadi and Simanungkalit, 2018). The extensive and large-sized roots of rubber trees can exert pressure on the soil, leading to increase a density and reduced pore space in the deeper soil layers, thereby decreasing the rate of water movement beneath the soil surface.

The lowest permeability value was found in the paddy field land use. This decline can be attributed to intensive land management practices, such as plowing. The study by Azurawati (2018) stated that soil tillage using a plow with more than one pass that significantly impact on the physical properties of the soil and causes soil compaction. This can lead to change in soil structure, reduced porosity, and increased bulk density. As a result, soil permeability becomes slower due to the smaller size of soil pores and the soil texture becoming more claylike (Mulyono *et al.*, 2019). In peat soils, this can lead to the oxidation of the peat layer and an increased rate of subsidence, ultimately threatening the long-term sustainability of the land. The soil permeability values in the results above illustrated how differences in land management practices can affect the physical properties of peat soils. Peat soils are highly sensitive to change in pressure and soil structure; therefore, alterations in land management practices can lead to significant variations in soil permeability. If not managed properly, peatlands can undergo severe degradation, including soil subsidence and increased risk of fire. Thus, it is essential to develop sustainable land management practices to ensure the long-term sustainability of peatland ecosystems.

The highest organic C content was observed in rubber plantations (33.68%), while the lowest was in paddy fields (9.6%). Oil palm plantations and

paddy fields had more mature peat (sapric), whereas rubber plantations and shrubland maintained more natural peat conditions. As a type of soil predominantly composed of organic materials, peat soil has an organic carbon content that is directly proportional to the amount of organic matter it contains (Siregar, 2017). Both in the topsoil and subsoil layers, Rubber plantations exhibited the highest concentrations of organic carbon and organic matter compared to other land use types, followed by Shrubland. In contrast, Paddy fields showed the lowest content, followed by Oil palm plantations and largely influenced by differences in land management practices and the dominant vegetation in each land use type. Rubber and Shrubland areas, which are generally less disturbed, allow for greater accumulation of organic matter.

This accumulation is further supported by the presence of leaf litter and relatively high plant biomass, both of which contributed to increase the organic carbon and organic matter content in the soil. The study by Hermansah *et al.* (2023) stated that land with permanent vegetation, such as rubber plantations or forests, tended to be richer in organic carbon as compared to land that is frequently cultivated, such as paddy fields. This is because less frequently cultivated land that using more time to accumulate organic matter and maintains a stable microbial decomposition process, thus increasing the organic carbon content in the soil. This is supported by research findings that rubber, Oil Palm, and Shrubland areas have C-organic content above 12%, meeting the minimum organic carbon criteria for peatland.

Analysis using Partial Least Squares Structural Equation Modeling, demonstrated that land use was significantly affected peat soil's physical properties, particularly bulk density, total pore space, permeability, and water content. Peat maturity level is served as an important indicator in assessing the physical and chemical characteristics of peat soils, which in turn influences how the land is managed and utilized. The peat maturity measurements also provided insights into the decomposition process of organic matter under each land use type. This information can be used as a reference for determining land suitability for various agricultural or plantation purposes. The maturity of peat soil can be measured by the degree of decomposition of the organic material it is contained. Based on research conducted on various types of peatlands, the results showed that overall, the peat soils are dominated by sapric peat. Only the peat at the topsoil layer in rubber land is classified as hemic.

Peat soil in rubber land at the topsoil layer showed lower maturity, indicated by a relatively high fiber content, ranging from one-third to two-thirds of the original material. It may be due to the continuous contribution of organic matter from the rubber vegetation through leaf litter and root decay. The roots of rubber trees also showed low down the decomposition process, resulting in soil

that retained a high amount of fiber. Permata (2016) explained that rubber vegetation can add organic material and slow the decomposition of peat soil through the contribution of decomposing plant parts. At a depth of 20–40 cm, the peat soil in rubber land is classified as sapric, where the remaining fibers are found to be minimal and the organic material, which is difficult to distinguish, due to the longer time and more advanced decomposition process in the deeper layer. The variation in peat thickness can occur due to several factors, such as vegetation type, land management systems, and local environmental conditions. In rubber plantations, the greater peat thickness may result from the continuous accumulation of organic material from fallen leaves and branches of rubber trees, leading to peat buildup. The anaerobic nature of peat soils is characterized by limited oxygen availability, which plays a crucial role in maintaining the stability of peat layer thickness.

The low load-bearing capacity is influenced by the low bulk density and high Porosity of peat (Dariah *et al.*, 2014) which further increases the likelihood of plants lodging, especially in deep peat areas such as those found in Rubber plantations. Conversely, paddy fields and oil palm plantations exhibit shallower peat thickness. In paddy fields, management practices involving waterlogging and soil tillage can accelerate the decomposition of organic matter, thereby reducing peat accumulation. Continuous flooding can influence oxidation processes, leading to a decrease in organic matter content and peat thickness. Oil palm plantations, on the other hand, tend to have aggressive root systems and high fertilizer uptake, which can disrupt the organic matter balance and accelerate decomposition (Rahayu *et al.*, 2021). Shrubland has the highest peat thickness, although it still falls within the moderate category. This occurs because shrubland areas are the least managed. Degraded peatlands, including those that are rarely managed or abandoned, tend to have greater peat thickness. Low water discharge and improper human activities in peatland management lead to the accumulation of poorly decomposed organic material, thereby increasing peat thickness (Masganti *et al.*, 2017).

Based on field observations conducted across various land use types in Sukaraja District, Seluma Regency, peat thickness varies depending on the type of land use. Environmental conditions, plant community types, and anthropogenic activities are contributing factors to the differences in thickness of the soil layers. Shrubland has the highest peat thickness, although it still falls within the moderate category. This occurs because shrubland areas are the least managed. Degraded peatlands, including those that are rarely managed or abandoned, tend to have greater peat thickness. Low water discharge and improper human activities in peatland management lead to the accumulation of

poorly decomposed organic material, thereby increasing peat thickness (Masganti *et al.*, 2017).

The variation in peat thickness can occur due to several factors, such as vegetation type, land management systems, and local environmental conditions. In Rubber plantations, the greater peat thickness may result from the continuous accumulation of organic material from fallen leaves and branches of Rubber trees, leading to peat buildup. The anaerobic nature of peat soils, characterized by limited oxygen availability, plays a crucial role in maintaining the stability of peat layer thickness. Peat depth plays a significant role in influencing soil bearing capacity. Greater peat depth is often associated with higher fiber content and softer texture, especially in immature peat (Hamdani, 2020). This condition makes the soil less stable and more difficult to support crops planted on it. Rubber trees, as plantation crops that require good soil stability for their root systems, can be affected by this condition, which is often indicated by leaning Rubber trees on peatlands. The low load-bearing capacity is influenced by the low bulk density and high Porosity of peat (Dariah *et al.*, 2014) which further increases the likelihood of plants lodging, especially in deep peat areas such as those found in Rubber plantations.

Conversely, paddy fields and oil palm plantations exhibit shallower peat thickness. In paddy fields, management practices involving waterlogging and soil tillage can accelerate the decomposition of organic matter, thereby reducing peat accumulation. Continuous flooding can influence oxidation processes, leading to a decrease in organic matter content and peat thickness. Oil palm plantations, on the other hand, tend to have aggressive root systems and high fertilizer uptake, which can disrupt the organic matter balance and accelerate decomposition (Rahayu *et al.*, 2021).

### **Conflicts of interest**

The authors declare no conflict of interest.

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