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DIFFERENCES IN CHARACTERISTIC OF SPODOSOLS, INCEPTISOLS, AND ULTISOLS TOWARDS OIL PALM PRODUCTIVITY

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Abstract: A region is generally composed of various soil types with different characteristics and fertility levels, causing variation in land suitability classes and oil palm production. Identifying soil characteristics can be used as a consideration in oil palm cultivation management to improve existing limiting factors for maximum production benefits. Therefore, this research aimed to carry out soil classification by identifying characteristics and land suitability of different soil orders, with a particular focus on TM 15 oil palm plantation land. Characteristics identification includes morphological observations and analysis of physical properties, while nutrient status was determined based on composite samples from 30 boreholes. Production data, consisting of fresh fruit bunch (FFB) productivity history (in t ha^{-1}) of oil palm over the past 10 years was collected from nine selected sample blocks concurrent with the identification observations. The results showed that the physical characteristic primarily distinguishing the soil orders was texture, significantly impacting oil palm production in Spodosols. Based on the analysis, Spodosols were found to have the lowest nutrient status, while Ultisols and Inceptisols had the highest nutrient status. The best suitability

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class for oil palm cultivation was found in Inceptisols, followed by Ultisols and Spodosols, which had the lowest suitability class due to the main limiting factors of sandy texture and poor drainage. This was evidenced by the average productivity of Inceptisols being 55% higher than that of Spodosols over 10 years. The average productivity of Ultisols was 28% lower compared to Inceptisols but 21% higher compared to Spodosols.
Keywords: marginal land; land suitability; palm oil productivity.
2020 AMS Subject Classification: 92C80.

1. INTRODUCTION

Oil palm is a frontrunner plantation crop and the largest export commodity in Indonesia, reaching 27.5 million tons in 2023. This figure marks a 4.8% increase from 2022, where 26.22 million tons were recorded [1]. In 2021, the export value of palm oil products reached USD 28.68 billion, representing a 53.4% increase from USD 18.69 billion in 2020 [2]. Oil palm plantations in Indonesia became the largest globally in 2021, covering an area of 16.83 million hectares with oil palm fresh fruit bunch (FFB) productivity reaching 14.34 tons ha^{-1} [3]. However, productivity of crude palm oil (CPO) was 2.68 tons ha^{-1} [2], falling significantly below the potential productivity of 7-9 tons ha^{-1} $year^{-1}$ [4].

Low productivity can be influenced by several factors, particularly the prevalence of oil palm plantations on marginal land [3], and low fertility of the soil [5]. Furthermore, land suitability, which refers to the optimum conditions required by plants for production, also affects productivity. The lower the land suitability class, the greater the limiting factors for growth and production [6]. Indonesia is an archipelagic country with complex geology, topography, climate, rainfall patterns, and water footprint [7], translating to diverse parent materials, soil orders, characteristics, and fertility levels. Parent materials, originating from weathering of rocks, impart distinct chemical content to the soil. The formation process comprised various physical, chemical, and biological reactions. These reactions shape soil properties. Parent materials with fine texture form soil with high organic matter content, while those with coarse texture contain lower organic matter [5].

In Indonesia, at least 10 soil orders out of 12 have been identified, namely Histosols, Entisols, Inceptisols, Andisols, Mollisols, Vertisols, Alfisols, Ultisols, Spodosols, and Oxisols [8]. Each soil order has different statuses and fertility levels, with Spodosols reportedly having lower pH and cation exchange capacity (CEC) compared to Inceptisols and Ultisols [9]. According to Sukarman et al. [10], Spodosols have lower nutrients including low levels of nitrogen (0.06%), low phosphorus (98 ppm), very low potassium (0.06%), and magnesium (0.19 Meq 100 g^{-1}). In comparison, Ultisols have low nitrogen content (0.06%), very high phosphorus (325 ppm), very low potassium (0.16%), and magnesium (0.24 Meq 100 g^{-1}).

Aside from fertility, differences in soil orders also affect oil palm production. In this context, oil palm on Spodosols has productivity of 16.30 tons ha^{-1} yr^{-1}, which is 31% lower than Ultisols [10]. Analysis of productivity comparison over 12 years showed that Ultisols produced the best yield at 23.5 tons ha^{-1} yr^{-1}, followed by Histosols at 20.09 tons ha^{-1} yr^{-1} (3% lower) and Entisols at 15.89 tons ha^{-1} yr^{-1} (33% lower) [10]. However, Spodosols and Entisols with sandy texture and macro pores struggle to retain water, causing oil palm plants on these soils to be more sensitive to drought (water deficit) [10].

Based on several previous research reports, differences in soil orders affect oil palm production when used as cultivation land. Therefore, it is important to identify the characteristics of each soil order and its influence on oil palm productivity.

Generally, land suitability assessment is conducted based on biophysical and ecological characteristics to evaluate agricultural potential [11]. Comparing suitability classes in each soil order and then juxtaposing with production data is crucial to bridge the gap between soil order and suitability class. Therefore, this research aimed to identify characteristics of three soil types and compare oil palm plantation yields in Bangkal village, Seruyan Raya sub-district, Seruyan Regency. The benefits include providing information on soil order and characteristics as well as the magnitude of differences in oil palm yields. This information is crucial as a consideration in oil palm cultivation land management.

2. Material And Methods

2.1. Research Location and Method Implementation

This research was conducted from June 2023 to November 2023 in Oil Palm Plantation in Bangkal Village, Seruyan Raya Sub-district, Seruyan Regency, covering an area of 7,519.3 ha (Figure 1). The activity entailed classification followed by identification of characteristics and land suitability of different soil orders. Characteristics identification was conducted on TM 15 oil palm plantation land (15-year-old plantation) or oil palm land planted in 2006. Subsequently, historical production data from the past 10 years was used to assess the influence of soil order and characteristics differences on production.

2.2. Research Procedure

Soil classification was conducted in three main stages including pre-survey, survey, and post-survey. The pre-survey included creating a basic map using geological, slope, existing soil type maps, and company data as references. The survey was carried out by digging soil profiles, mini pits, and boreholes at a semi-detailed level. Post-survey included analyzing the survey results by classifying the soil based on the USDA system and creating Soil Mapping Units (SMUs).

Soil characteristics identification was performed by creating profiles and collecting samples. The number of identification samples was determined based on the same oil palm planting year (2006) for each soil type found including Inceptisols, Ultisols, and Spodosols. The sample units consisted of entire planting blocks, namely nine including (D16, D20, D24: Spodosols), (I21, I22, 123: Inceptisols), and (K24, M24, N23: Ultisols). The purpose of these entire block samples was to obtain accurate historical production values. The identification included observing horizon characteristics (soil morphology), texture characteristics, nutrient status, and land suitability classes. Soil morphology and texture were observed in soil profiles, while nutrient status was determined from composite samples of 30 soil borehole points (Figure 1).

The soil samples were analyzed at the Environmental Management Unit (EMU) Laboratory, R&D Division, PT. Mustika Sembuluh, Wilmar, Seruyan Regency, Central Kalimantan. The analyses conducted included soil texture, pH, organic carbon, total nitrogen, Bray P, total phosphorus, basic cations (K, Ca, Mg, Na), CEC, base saturation (BS), as well as aluminum (Al) and iron (Fe) content in the soil. The results of characteristics identification were used to assess the land suitability class in the sample blocks. The assessment was performed using the matching method, which entailed matching field land quality and characteristics as parameters with the criteria of suitability classes compiled based on the requirements of land use or crop growth evaluated [6].

Production data, consisting of FFB productivity (t ha^{-1}) of oil palm over the past 10 years was collected from the nine selected sample blocks identified during characteristics identification observations.

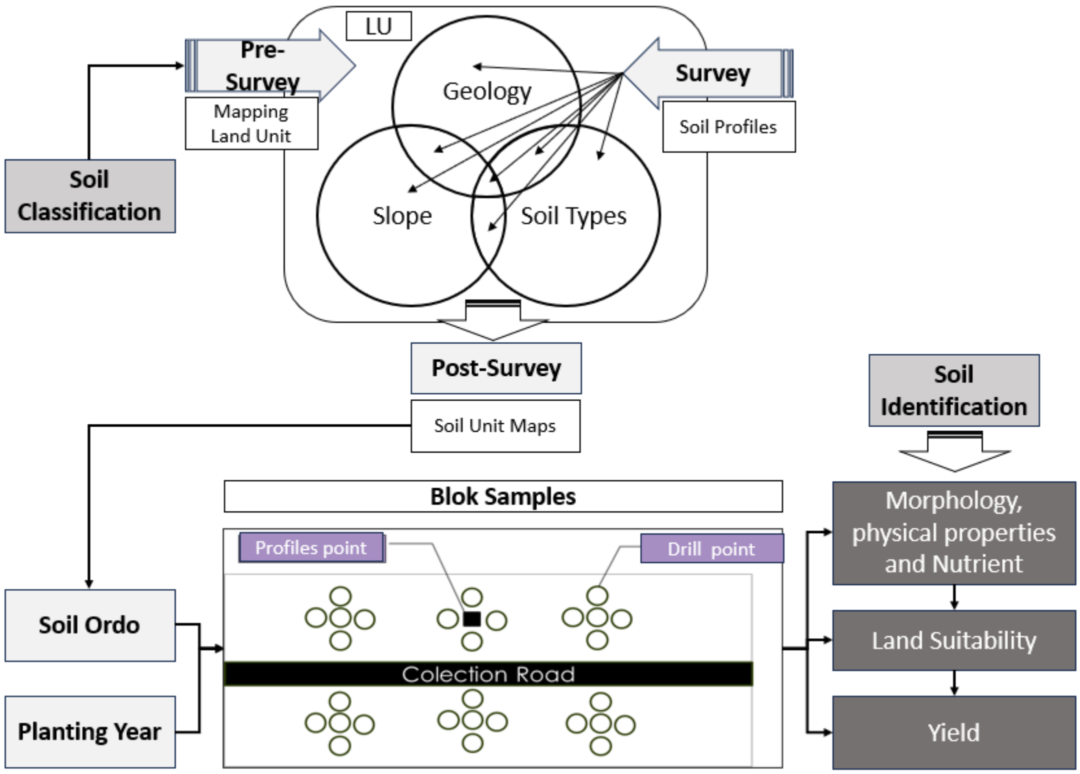

Figure 1. Research Flow and Sample Collection

2.3. Data Analysis

The analysis of land suitability classes was conducted using the criteria from Djaenudin et al. [6], to determine differences between each soil order. A t-test was conducted to assess differences in productivity between soil types. Furthermore, a correlation test was performed between productivity data and soil nutrient status to determine the influence of the relationship.

3. Results And Discussion

3.1. Soil Morphology and Classification

The results of soil classification at the research site are presented in SMUs (Figure 2). A total of three soil orders were found at the research site, namely Spodosols, Ultisols, and Inceptisols covering an area of 2,245.6 ha or 29.9%, 5,062 ha or 67.3%, and 211.7 ha or 2.8% respectively. The area of Inceptisols was the smallest and was only found in three blocks. This explains why the number of identification samples is only three blocks for each soil order.

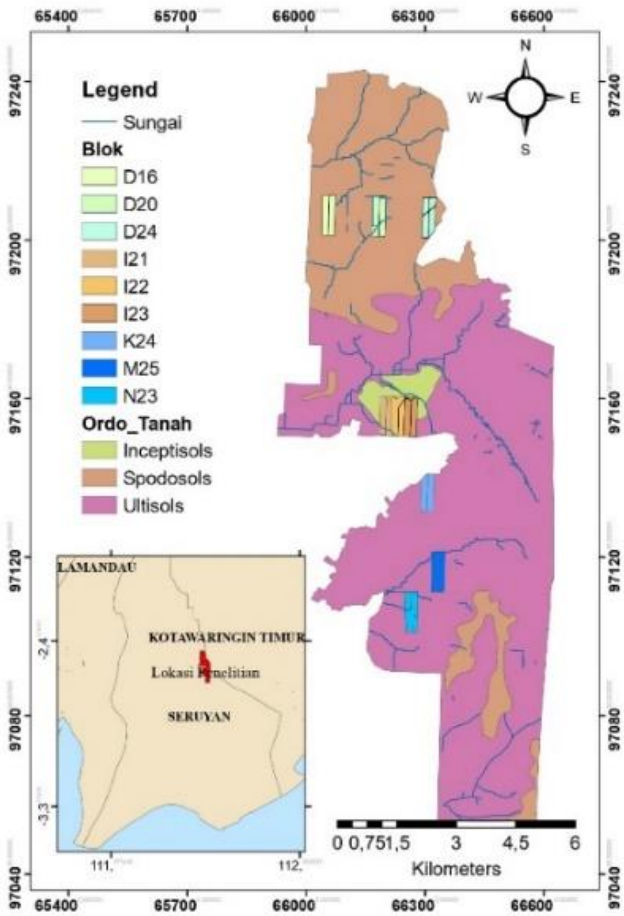

Figure 2. Soil Order Map of the Research Location

The results of Spodosols classification in Table 1 showed the morphological characteristics including the presence of complex genetic horizons, namely A, E, Bhs, and C horizons. The E horizon had a bright color with a value > 6, showing that the horizon belonged to the Albic class. Meanwhile, the dark color and firm consistency distinguished Bhs as a Spodic horizon. The Albic E horizon found was quite thick, as well as the Spodic horizon, reaching more than 70cm in thickness. A distinct physical characteristic was that almost all horizons had sandy texture, mainly in the A and E with loose to very loose consistency.

Table 1. Spodosols Profiles Description

Horizon	Soil Depth (cm)	Soil Color	Soil Texture	Soil Structure and Consistency
Spodosols Blok D16				
A	0-11	7.5 YR 2.5/1	Sandy Loam	Sub angular blocky, very friable
E_1	11-(24/34)	10 YR 8.5/2	Sand	Single grain, loose
E_2	34-55	10 YR 9/1	Sand	Single grain, loose
E_3	55-70	7.5 YR 9/1	Loamy Sand	Single grain, loose
Bhs_1	70-82	7.5 YR 3/2	Loamy Sand	Angular Blocky, friable
Bhs_2	82-96	10 YR 2/1	Loamy Sand	Angular Blocky, friable
2BE	96-115	7.5 YR 6/1	Loamy Sand	Angular Blocky, firm
$2Bhs_1$	109-128	7.5 YR 3/2	Sand	Angular Blocky, very firm
$2Bhs_2$	128-143	7.5 YR 2.5/2	Loamy Sand	Angular Blocky, very firm
2BC	143-162	7.5 YR 2.5/2	Loamy Sand	Angular Blocky, very firm
2C	162-175	5 YR 2.5/2	Sand	Sub angular blocky, very firm
Spodosols Blok D20				
A	0-8	10 YR 3/1	Sandy Loam	Single grain, loose
E	8-34	10 YR 6/1	Sand	Single grain, loose
BE	34-63	10 YR 3/1	Sand	Single grain, loose
Bhs_1	63-115	10 YR 2/1	Sand	Angular Blocky, very firm
2Bhs	115-153	7.5 YR 2.5/2	Loamy Sand	Angular Blocky, very firm
2C	153-175	7.5 YR 2.5/1	Sand	Sub angular blocky, firm
Spodosols Blok D24				
A	0-18	10 YR 3/1	Sandy Loam	Sub angular blocky, very friable
E_1	18-29	10 YR 8/1	Sand	Single grain, loose
EB	29-39	7.5 YR 5/2	Loamy Sand	Sub angular blocky, friable
Bw	39-49	10 YR 5/1	Sandy Loam	Sub angular blocky, friable
2BE	49-(64/82)	10 YR 8.5/2	Loamy Sand	Angular Blocky, firm
$2Bhs_2$	64-(90/107)	10 YR 2/2	Sandy Loam	Angular Blocky, very firm
$2Bhs_2$	90-150	10 YR 5/4	Sandy Loam	Angular Blocky, very firm

Albic and Spodic are the main diagnostic horizons of Spodosols [12]. The Spodic horizon is formed in the dark-colored (reddish-brown, dark brown, black) illuvial horizon (Bhs), which is rich in Al, Fe, and organic matter [13]. Meanwhile, E is an eluviation horizon that experiences leaching of clay, humus, or nutrients [12]. In this eluviation process, these materials are subsequently accumulated and form the Spodic horizon, a process referred to as podzolization [13]. Consequently, the E horizon becomes pale gray (albic) in color [13]. Spodosols are parented by sandy material and are naturally infertile, mostly found in forested areas [14].

Table 2. Inceptisols Profiles Description

Horizon	**Soil Depth (cm)**	**Soil Color**	**Soil Texture**	**Soil Structure and Soil Consistency**
Inceptisols Block I21				
A	0-3	7.5 YR 3/3	Clay	Medium sub angular, firm
Bw	3-33	5 YR 4/4	Clay	Medium sub angular, firm
Bw2	33-66	5 YR 3/4	Clay	Sub angular blocky, friable
BC	66-105	5 YR 4/4	Clay	Sub angular blocky, friable
C	105-155	5 YR 5/4	Clay	Sub angular blocky, friable
Inceptisols Block I22				
A	0-(13/26)	5 YR 3/4	Clay	Medium sub angular, friable
A2	0-32	7.5 YR 2.5/2	Clay	Sub angular blocky, friable
A3	13-32	7.5 YR 4/3	Clay	Sub angular blocky, friable
Bw	32-(56/71)	7.5 YR 3/4	Clay	Sub angular blocky, firm
BC	71-100	5 YR 3/4	Clay	Sub angular blocky, firm
BC	56-133	5 YR 3/4	Clay	Sub angular blocky, firm
C	133-155	5 YR 3/4	Clay	Sub angular blocky, firm
Inceptisols Block 123				
A	0-12	10 YR 3/2	Clay	Sub angular blocky, friable
Bw	12-39	7.5 YR 6/5	Clay	Sub angular blocky, friable
Bw	39-70	7.5 YR 5/5	Clay	Angular Blocky, firm
BC	70-120	7.5 YR 4/4	Clay	Angular Blocky, firm
C	120-150	7.5 YR 4/4	Clay	Angular Blocky, firm

The results of Inceptisols classification are presented in Table 2. Simple genetic horizons were found namely A, Bw, and C. The Bw horizon shows that new soil development has occurred, where development is limited to alterations in consistency or color without significant texture changes. It is also an indicator of the cambic horizon and recognized as the main characteristic of Inceptisols. Inceptisols found in this research have a clay texture with the absence of differences across all horizons.

Inceptisols found have relatively thick cambic horizons with a consistency ranging from loose to firm. Another common name is young soils due to the new profile development process [15]. Inceptisols typically form on gently to moderately sloping terrain and have characteristic cambic or kandic horizons [13]. The cambic horizon is formed due to physical alteration, transformation, chemical translocation processes, or a combination of both [12].

Table 3. Ultisols Profiles Description

Horizon	**Soil Depth (cm)**	**Soil Color**	**Soil Texture**	**Soil Structure and Consistency**
Ultisols Block K24				
A	0-8	10 YR 4/1	Sandy Clay Loam	Sub angular blocky, firm
Bt1	8-72	7.5 YR 4/6	Sandy Clay	Angular Blocky, firm
Bt2	72-115	7.5 YR 6/8	Clay	Angular Blocky, firm
Btv	115-150	7.5 YR 6/6	Clay	Angular Blocky, very firm
Ultisols Block M25				
A	0-10	5 YR 3/2	Clay Loam	Sub angular blocky, friable
Bw	10-23	7.5 YR 4/4	Clay Loam	Angular Blocky, firm
Bt1	10-65	5 YR 5/8	Clay Loam	Angular Blocky, firm
Bt2	65-86	2.5 YR 5/8	Clay	Angular Blocky, firm
Btg	86-125	2.5 YR 4/8	Clay	Angular Blocky, very firm
Ultisols Block N23				
A	0-8	10 YR 3/3	Sandy Clay Loam	Sub angular blocky, friable
Bt1	8-(21/48)	10 YR 4/6	Clay	Sub angular blocky, firm
Bt2	21-52	7.5 YR 5/6	Clay	Sub angular blocky, firm
Bt3	52-56	7.5 YR 5/8	Clay	Sub angular blocky, firm
Btv1	56-100	5 YR 5/8	Clay	Angular Blocky, firm
Btv2	100-150	5 YR 6/8	Clay	Angular Blocky, very firm

The results of Ultisols classification are presented in Table 3. Characteristics of the genetic horizons found include A, Bt, Btg, and Btv. The Bt horizon was found in all soil profiles showing advanced soil development where significant clay illuviation has occurred. This was indicated by differences in soil texture between the A and Bt horizons. Bt is a sign of argillic horizons and is also the main characteristic of Ultisols with low BS. A significant physical characteristic of Ultisols is the significant texture difference between the upper and lower layers, as well as a firm consistency.

Ultisols have advanced development, characterized by the presence of Argillic or Kandic horizons that experience increased clay content (illuviation) in soil pedons with low base saturation conditions (BS < 35%) [8]. In this research, Ultisols were found to have thick argillic horizons with clay parent material. The argillic horizon normally represents a subsurface with significantly higher percentages of clayey silicate than the soil material above, showing evidence of clay illuviation [12]. Meanwhile, the kandic horizon is an illuviation dominated by weak clay activity, with coarse-textured soil below [16].

Morphologically, differences between the three soil orders found lie in the diagnostic horizons identified. In Spodosols, the Albic E and Spodic B horizons were found, while Inceptisols were discovered in the Bw genetic and characteristic cambic horizon. The Bt genetic horizon with argillic characteristics was found in Ultisols. Furthermore, the parent materials forming the soil in the three soil orders were also different. The parent material in Spodosols is sandy rock, while Inceptisols and Ultisols are clay rock. This difference leads to significantly different texture characteristics in Spodosols compared to other soil orders.

3.2. Soil Nutrient Status, Land Suitability, and Production

The research site was found to have three dominant soil orders, namely Spodosols, Inceptisols, and Ultisols. The observations of soil nutrient status in Table 4 showed that the highest average pH was found in Inceptisols, with a value of 4.80, followed by Spodosols at 4.77 and Ultisols at 4.52. The average BS, total nitrogen (N), and available phosphorus (P) showed a similar pattern. The KB in Inceptisols was 48.37%, followed by Spodosols at 33.53% and Ultisols at 22.23%. The average N content was 2.7 g kg^{-1}, 1,2 g kg^{-1}, and 0,9 g kg^{-1}, while the average available P content was 124 mg kg^{-1} P_2O_5, 35 mg kg^{-1} P_2O_5, and 7 mg kg^{-1} P_2O_5 respectively.

The highest average soil organic carbon content was found in Inceptisols, with a value of 55 g kg^{-1}, followed by Ultisols at 23.3 g kg^{-1} and Spodosols at 7.7 g kg^{-1}. CEC, K, Mg, Ca, and Na content in the soil followed a similar pattern. CEC in Inceptisols, Ultisols, and Spodosols were 15.43, 12.63, and 3.93 cmol kg^{-1}, while the potassium (K) content was 0.76, 0.17, and 0.14 cmol kg^{-1}, respectively. Furthermore, the average magnesium (Mg) content was 3.40, 0.87, and 0.30 cmol kg^{-1}, respectively. The average calcium (Ca) content in Inceptisols, Ultisols, and Spodosols was 3.64, 1.51, and 0.57 cmol kg^{-1} while the average sodium (Na) was 0.16, 0.14, and 0.07 cmol kg^{-1} respectively.

Table 4. The Average Soil Nutrient Status at A Depth of 20 Cm

Parameter	Unit	Soil Order		
		Spodosols	Inceptisols	Ultisols
pH	*H_20*	4.77	4.80	4.52
pH	*KCL*	4.49	4.56	4.21
C-Organik	*g kg^{-1}*	7.7	55	23.3
CEC	*cmol kg^{-1}*	3.93	15.43	12.63
N	*g kg^{-1}*	1.2	2.7	0.9
P Bray	*Mg kg^{-1}*	35	124	7
P	*Mg kg^{-1}*	232	1,392	307
KB	*%*	33.53	48.37	22.23
K	*cmol kg^{-1}*	0.14	0.76	0.17
Mg	*cmol kg^{-1}*	0.30	3.40	0.87
Ca	*cmol kg^{-1}*	0.57	3.54	1.61
Na	*cmol kg^{-1}*	0.07	0.16	0.14

Differences observed in nutrient content for each soil order were attributed to several factors. Spodosols, characterized by a sandy texture, have high leaching rate leading to low nutrient status in the upper layers. The nutrient status was lower compared to Ultisols and Inceptisols. Additionally, Spodosols have the highest proportion of sand with the least amount of clay particles. The sandy texture with large-sized pores translates to rapid particle conductivity as well as low nutrients and water-retaining capacity [17]. According to Safitri et al. [18], sandy soil texture reduces soil CEC and water retention capacity, providing a significant opportunity to lose nutrients. The organic carbon content in Spodosols is also the lowest among the other orders. In addition to the influence of sandy texture, the low organic matter content in Spodosols results in a reduction of organic colloids (humus), which are the source of soil's negative charge, reducing the exchangeable positive charge of the soil [19]. Tiemann et al. [20], reported that leaching and evaporation of N nutrients in sandy clay soils can occur up to 40% within 7 days after fertilizer application and may increase lighter textures.

Inceptisols, characterized by the best nutrient status have a clay texture, yielding the highest CEC compared to other soils. Soil CEC affects nutrient availability, which is related to the cation absorption capacity [21]. Organic carbon is more abundant in Inceptisols compared to other orders, contributing to the increase in soil CEC [22].

Ultisols are often referred to as soils with low fertility due to low CEC, BS, and pH pH [23]. Based on the results, this soil order had the lowest BS and pH as shown in Table 4. Widiatmaka et al. [24], described also Ultisols as old soils with high acidity and aluminum exchange capacity, while the low pH and BS values were due to significant leaching. According to Fageria & Nascente. [25], soil acidity can be caused by the leaching of bases such as calcium, magnesium, potassium, and sodium from the profile. The propensity for leaching base cations in areas with high rainfall [26], further accentuates soil acidity [25].

Nutrient status can affect land suitability classes, measured in this research based on pH, organic carbon, N, P, CEC, BS, soil texture, and drainage, as shown in Table 5. Climate factors such as rainfall and temperature were not considered, given the proximity of the research location, which shares the same climatic factors.

Table 5. Land Suitability in the Sample Block

Soil Order	**Block**	**pH**	**Organic Carbon**	**N**	**P-Bray**	**CEC**	**BS**	**Drainage Class**	**Texture**	**Conclusion**
Spodosols	D16	S2	S2	S1	S1	S2	S2	N	N	Nrc, oa
Spodosols	D20	S2	S3	S1	S2	S2	S2	N	N	Nrc, oa
Spodosols	D24	S2	S1	S1	S1	S1	S3	N	N	Nrc, oa
Mean		**S2**	**S3**	**S1**	**S1**	**S2**	**S3**	**N**	**N**	**Nrc, oa**
Inceptisols	I21	S2	S1	S1	S1	S1	S2	S1	S2	S2nr, rc
Inceptisols	I22	S2	S1	S1	S1	S1	S2	S1	S2	S2nr, rc
Inceptisols	I23	S2	S1	S1	S1	S1	S3	S1	S2	S3nr
Mean		**S2**	**S1**	**S1**	**S1**	**S1**	**S2**	**S1**	**S2**	**S2nr, rc**
Ultisols	K24	S2	S1	S1	S2	S1	S3	S2	S2	S3nr
Ultisols	M25	S2	S1	S1	S2	S1	S3	S2	S2	S3nr
Ultisols	N23	S2	S1	S2	S3	S1	S3	S2	S2	S3nr
Mean		**S2**	**S1**	**S1**	**S2**	**S1**	**S3**	**S2**	**S2**	**S3nr**

Productivity data presented in Figure 3, was measured as FFB production per hectare per year (tons ha^{-1}) over the past 10 years. Based on the results, productivity trend has been similar across all soil orders. The highest production was found in Inceptisols, with an average of 26.84 tons ha^{-1} FFB. Ultisols have a production of 21.66 tons ha^{-1} FFB, while Spodosols have the lowest production, averaging 17.63 tons ha^{-1} FFB.

The yield (ton ha^{-1} FFB) comparison across the three soil orders showed statistically significant differences. The comparison was based on identical management practices, climate, and planting years. Therefore, it was concluded that differences in soil orders significantly influenced the yield gap of oil palm. Each soil order possesses distinct characteristics, with classification being based on the level of development [12].

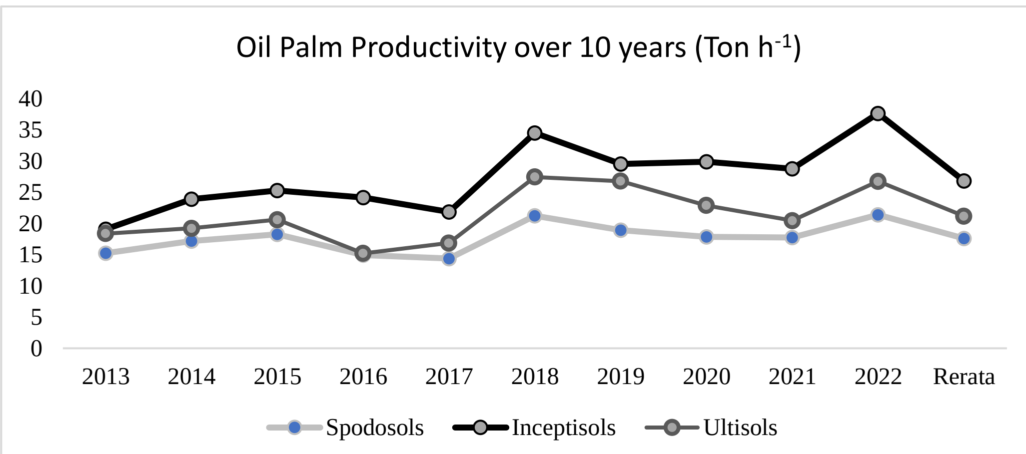

Figure 3. Oil Palm Yield in Different Soil Orders over the Last 10 Years

The land suitability class for Spodosols was Nrc, oa, showing unsuitability for oil palm cultivation as evidenced by the lowest production over the last 10 years. The limiting factors for cultivation were soil texture and drainage class. The land suitability class for Ultisols was S3nr, suggesting marginal suitability for oil palm cultivation and the limiting factor was low soil BS. Meanwhile, the land suitability class for Inceptisols was S2nr, rc, showing suitability for oil palm cultivation. The factors that could limit production in the soil were high clay texture, acidic pH, and low soil BS.

Generally, Spodosols are formed from the parent material of sandy rocks, contributing to a predominantly sandy texture [13] [27]. Subardja et al. [8], suggested that oil palms are unsuitable for planting on sandy-textured soils such as Spodosols. The correlation value (Table 6) between yield and sand content was -81, showing a significant negative correlation. This suggests that higher sand content can decrease oil palm yield. According to Djaenudin et al. [6], land suitability refers to the optimum conditions plants require for production. The lower the land suitability class, the greater the limiting factor for growth and production.

Although Spodosols have the lowest nutrient status compared to other soil orders, the limiting factors were not explicitly stated. The identification of limiting factors is based on the most influential determinants affecting others. The sandy texture was the greatest limiting factor affecting many other growth and production determinants. According to Rintung et al. [28], land suitability shows the level of appropriateness for cultivating specific crops, measured based on the most limiting factor affecting the production.

As stated by Suwardi et al. [29], Spodosols are unsuitable for crop cultivation due to the sandy texture and spodic layer, which inhibit root penetration. Additionally, sandy soils experience higher water loss compared to finer-textured soils [30], leading to rapid drainage [31]. Bonsu. [32] stated in [33] that the most important soil property affecting evaporation, water retention capacity, and drainage was soil texture. Spodosols with hard spodic horizons often experience waterlogging during the rainy season, while sandy texture leads to drought in the summer and high erosion on sloping land [34]. This soil order has a very sandy upper horizon and low chemical fertility, leading to unsuitability for oil palm cultivation [4].

Soil with a sandy texture has low water-holding capacity and rapid drainage, potentially leading to drought stress, which can reduce production by up to 60% [35]. Darlan et al. [36], discovered that drought stress in young plants could cause delayed harvesting. Meanwhile, in mature plants, it could lead to a production decrease of up to 41%. Water stress reduces oil palm production through abortion, and low sex ratio values, both leading to a lower number of bunches per tree and a decrease in average bunch weight [4]. Riski [37] and Caraka et al. [38] added that stress affects vegetative growth including leaf area, new shoot growth, and shoot-root ratio. The impacts on generative growth include flower abnormalities, embryo abortion, as well as abnormal seed and fruit development.

The land suitability class of Ultisols in this research was S3, with the limiting factor being low BS. This particular soil order produces higher yields compared to Spodosols but lower than Inceptisols. Although the main limiting factor for Ultisols was BS soil, there was no significant correlation between yield and BS as depicted in Table 6. BS is related to the amount of exchangeable base cations in the soil, hence directly correlates to pH. The greater the amount of exchangeable base cations in the soil, the higher the BS and pH [39]. Soil pH affects the availability of phosphorus (P), with the nutrients being most available at a pH range of 4.5 - 6.5. In this research, the amount of P-Bray was directly proportional to pH, with lower pH corresponding to lower available P. In contrast to total phosphorus (P-total), which was lowest in Spodosols, the lowest P-Bray was found in Ultisols with the lowest pH.

Despite having the lowest available phosphorus content, Ultisols have better nutrient contents of potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) compared to Spodosols. Additionally, Ultisols were found to have a clay texture with relatively higher C-organic and CEC, reaching approximately 23.3 g kg^{-1}, and 12.63 cmol kg^{-1}, compared to Spodosols.

Table 6. Correlation Values of Yield and Soil Nutrient Status

Parameter	pH H_2O	pH KCL	C-Organic	N	P Bray	P	K	Mg	Ca	Na	CEC	KB	Sand	Dust	Clay
Correlation Values	0.3	0.26	0.88	0.68	0.57	0.79	0.61	0.72	0.77	0.59	0.78	0.46	-0.81	-0.29	0.94

This research data showed a significant correlation between Yield and P-Bray, P-total, K, Mg, Ca, Na, CEC, and soil clay content, with the most significant correlation occurring between yield with clay content and organic carbon (Table 6).

The soil order with the best nutrient status, land suitability class, and yield was Inceptisols. This soil was classified as an S2nr, rc, showing suitability class with limiting factors being pH, BS, and soil texture. Based on the results, Inceptisols produced 26.84 tons of FFB per hectare annually over 10 years. The S2 suitability class suggests that the limiting factors can be addressed by farmers with additional inputs and relatively inexpensive costs [6]. The improvable limiting factors include soil pH and BS, while clay texture cannot be improved.

The most distinguishing characteristic of the three soil orders at the research location closely related to oil palm yield was texture. Spodosols have a sandy soil texture accompanied by poor drainage, leading to the classification as N or unsuitable for oil palm cultivation. The sandy texture further affects water availability and soil nutrient status, causing a yield gap compared to other soil orders. Meanwhile, Ultisols, being older soils subjected to high levels of leaching, have the limiting factor of BS. This soil is characterized by high acidity with elevated clay content in the lower horizons due to long-term leaching. Ultisols also have an S3 or marginal suitability class, requiring high inputs to achieve optimal oil palm production. Inceptisols, characterized by young soils with soft consistency in each horizon, are suitable for oil palm cultivation. Despite originating from clay parent material, Inceptisols can yield high oil palm production.

4. CONCLUSION

In conclusion, three soil orders were identified in the research site namely Spodosols, Ultisols, and Inceptisols. The physical characteristic that most significantly differentiated these soils was texture, also considered the main limiting factor for palm oil production on Spodosols. Soil nutrient status results showed that Spodosols had the lowest nutrient status, followed by Ultisols, with Inceptisols having the highest. The best land suitability class for palm oil cultivation was found in Inceptisols, followed by Ultisols and Spodosols, which had the lowest suitability due to the main limiting factors of sandy texture and poor drainage. This was evidenced by the average productivity of Inceptisols, with a class of S1, being 55% higher over 10 years compared to productivity of Spodosols with a class of N. The average production of Ultisols with a class of S3 was 28%, which was lower compared to Inceptisols but 21% higher than Spodosols. There was a strong correlation between productivity and soil organic carbon, total nitrogen (N), P-Bray (P2O5), total phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sodium (Na), cation exchange capacity (CEC), as well as the amounts of clay and sand in the soil.

Further study may involve the deployment of web portal [40] and cloud computing [41] as we usher the era of agriculture 4.0 [42].

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests.

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