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Physicochemical characteristics of andisols and their correlation to potato yield based on land mapping units

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Abstract

The high phosphate retention in andisol soil is often associated with a decrease in potato yield. Additionally, identification of the physical and chemical characteristics of andisols and their correlation to potato yield through soil mapping units (SMUs) is necessary to facilitate field surveys. Therefore, this study aimed to identify the physicochemical characteristics of andisols with a focus on available phosphorus (P) and the correlation to potato production based on SMUs. The experiment was conducted in Karo District, North Sumatra, Indonesia, from July 2022 to February 2023. A descriptive-analytical method was used by overlaying maps of slope, soil types, and altitude until 10 SMUs were selected that were planted with potatoes. Soil physicochemical properties were identified, while Pearson correlation analysis was performed on available-P and potato yield using IBM SPSS software. The results showed that the silt and clay fractions positively correlated with available-P in andisols. All soil physical characteristics were categorized as very weak to weak in supporting potato yield. A total of four SMUs including 1, 5, 8, and 10 were found to have lower available-P and very low to moderate correlations with soil pH, organic-C, C:N ratio, cation exchange capacity (CEC), as well as total-P. Based on the results, potato yield could increase by 1.765 and 0.380 tons ha^{-1} through the addition of organic-C and C:N ratio in Karo District. Therefore, soil amendment is required as an alternative to improve andisols soil.

Keywords: andisols, correlations, potato yields, soil

Introduction

The potato plant (*Solanum tuberosum* L.) is one of the horticultural crops with export potential. According to data from Statistics Indonesia (2018), potatoes in Indonesia ranked fourth among horticultural crops with export potential totaling 0.92 thousand tons, following cabbage, shallots, and mushrooms. The production centers are spread across five provinces, namely East Java, Central Java, West Java, Jambi, and North Sumatra. Statistics Indonesia (2022), reported that North Sumatra contributes 9.90% of potato yield in Indonesia. Furthermore, as stated by Statistics of Sumatera Utara (2022), the largest planting area is located in Karo District, followed by Simalungun and Samosir. Data also shows a decrease in potato yield by 6.65% in 2022 from North Sumatra. This decrease needs to be studied from the perspective of soil science to guide farmers in potato cultivation, specifically in Karo District.

According to Local Government of Karo District (2023), the dominant soil type is andisols, followed by ultisols, litosols, grumusols, and alluvial. The distribution of andisols in potato cropping impacts growth and yield, particularly due to several issues, despite being rich in organic and mineral substances. Tarigan & Hanum (2019) found that potato yield in 27 villages of Karo District ranged from low to moderate, totaling 15 to 24 tons ha^{-1}. Sukarman & Dariah (2014) reported high phosphate retention (> 85%), making phosphorus unavailable to plants, with pH predominantly ranging from 4.5 to 6.5, the highest aluminum (Al_0) content, and organic-C ranging from 6 to 15%. Phosphate retention can be influenced by several soil physical characteristics such as bulk density (Neris et al., 2012), clay content (Andriamananjara et al., 2016; Arifin et al., 2022), silt content (Nishigaki et al., 2021), and others. Similarly, altitude and slope can affect the rate of organic matter weathering (Hu et al., 2018).

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Soil chemical characteristics play a significant role in phosphate retention, such as soil pH (Hashimoto et al., 2012), organic matter (Yan et al., 2013; Yang et al., 2019; Maritasari et al., 2022), C:N ratio (Anda & Dahlgren, 2020), etc.

The availability of phosphorus in andisols and the relationship with crop yield needs to be identified through the physicochemical characteristics based on Soil Mapping Units (SMUs) and then correlated. The use of SMUs aimed to group diverse land attributes including landforms, soil types, and vegetation, into homogeneous units to facilitate initial field surveys (Zonneveld, 1989). On the other hand, correlation analysis is necessary to determine the positive or negative relationship between soil physicochemical and available-P in relation to potato yield. Studies on identification and correlation based on SMUs have been conducted for agricultural commodities such as arabica and robusta coffee (Marbun et al., 2023; Marbun et al., 2020). However, the relationship between soil physicochemicals, available phosphorus, and potato yield on andisols in Karo District has not been studied. This study aimed to identify the physicochemical characteristics of andisols with a focus on available phosphorus and the correlation with potato yield based on SMUs.

Material and Methods

Study site and overlay methods

This study was conducted on potato cropping in Karo District, North Sumatra, Indonesia (**Figure 1**) from July 2022 to February 2023. Mapping overlay was performed between slope, altitude, and soil type, specifically andisols, to form SMUs. Based on the overlay results, 14 SMUs were formed (**Figure 2**). Slope mapping was clustered into 0-3; 3-8; 8-16; 16-30; and more than 30% categories, while altitude was divided into 300 m intervals above sea level (Figure 2A and 2B). The mapping results also indicated the presence of four soil types, namely andisols, inceptisols, mollisols, and ultisols (Figure 2C). An initial field survey was conducted to confirm potato cropping in these SMUs. The preliminary survey results showed that there were 10 SMUs with potato cropping covering an area of 81,740.86 ha, with the largest SMU found in SMU 4 (**Table 1**).

Study method and sampling technique

This study used an analytical descriptive method with purposive sampling. A total of three soil samples were taken from each location in the 10 SMUs selected, accompanied by coordinate points and climate data such as air moisture and temperature (**Table 2**). The air temperature and moisture at the study locations ranged from 15.4 to 22.2°C and 70.3 to 90.8%, respectively. Soil samples were collected using an auger to a depth of 0-20 cm, with 1 kg from each analyzed in the laboratory to measure physicochemicals. Data on harvested area and potato yield were collected through interviews with farmers from each location.

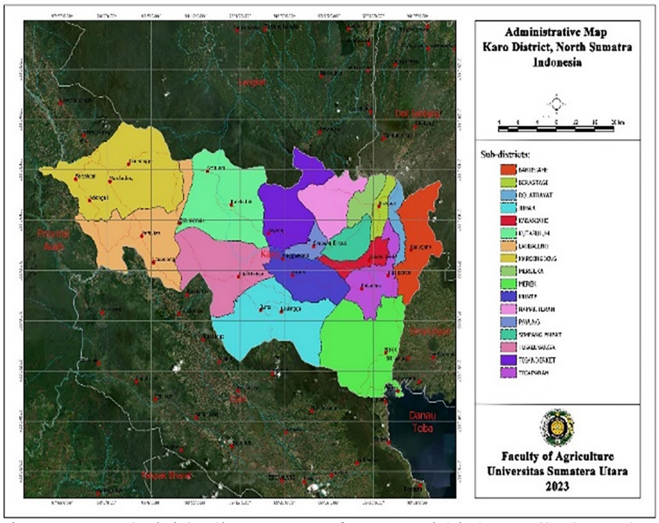

Figure 1. Administrative map of Karo District, North Sumatra, Indonesia.

Table 1. A preliminary survey from 14 SMUs with potato cropping in Karo District, North Sumatra, Indonesia.

SMUs overlay	Crops	SMUs selected	Land area (ha)
1	Potato	1	175.95
2	Potato	2	6,654.74
3	Eggplant, Chilli Pepper	-	-
4	Potato	3	14,958.60
5	Potato	4	37,409.46
6	Potato	5	916.29
7	Cabbage	-	-
8	Potato	6	637.20
9	Potato	7	16,116.58
10	Potato	8	2,713.74
11	Shallot, Hot Pepper	-	-
12	Potato	9	956.08
13	Chilli Pepper, Shallot	-	-
14	Potato	10	1,202.22
Total			81,740.86

Soil physicochemical analysis

Soil physics analysis included moisture, water content, and texture fractions of the soil, as well as slope and altitude. Soil moisture measurement was conducted using a digital tool called a soil meter, while the soil water content and texture fractions were measured in the laboratory using gravimetric and hydrometer methods, respectively. The chemical characteristics measured included pH using the electrometric method (H_2O and KCl 1 M), and organic-C with the Walkley and Black method. Furthermore, total-N was measured with the Kjeldahl method, and total-P was assessed using the HNO_3 extraction method. Available-P was measured through the Bray II method and total-K was

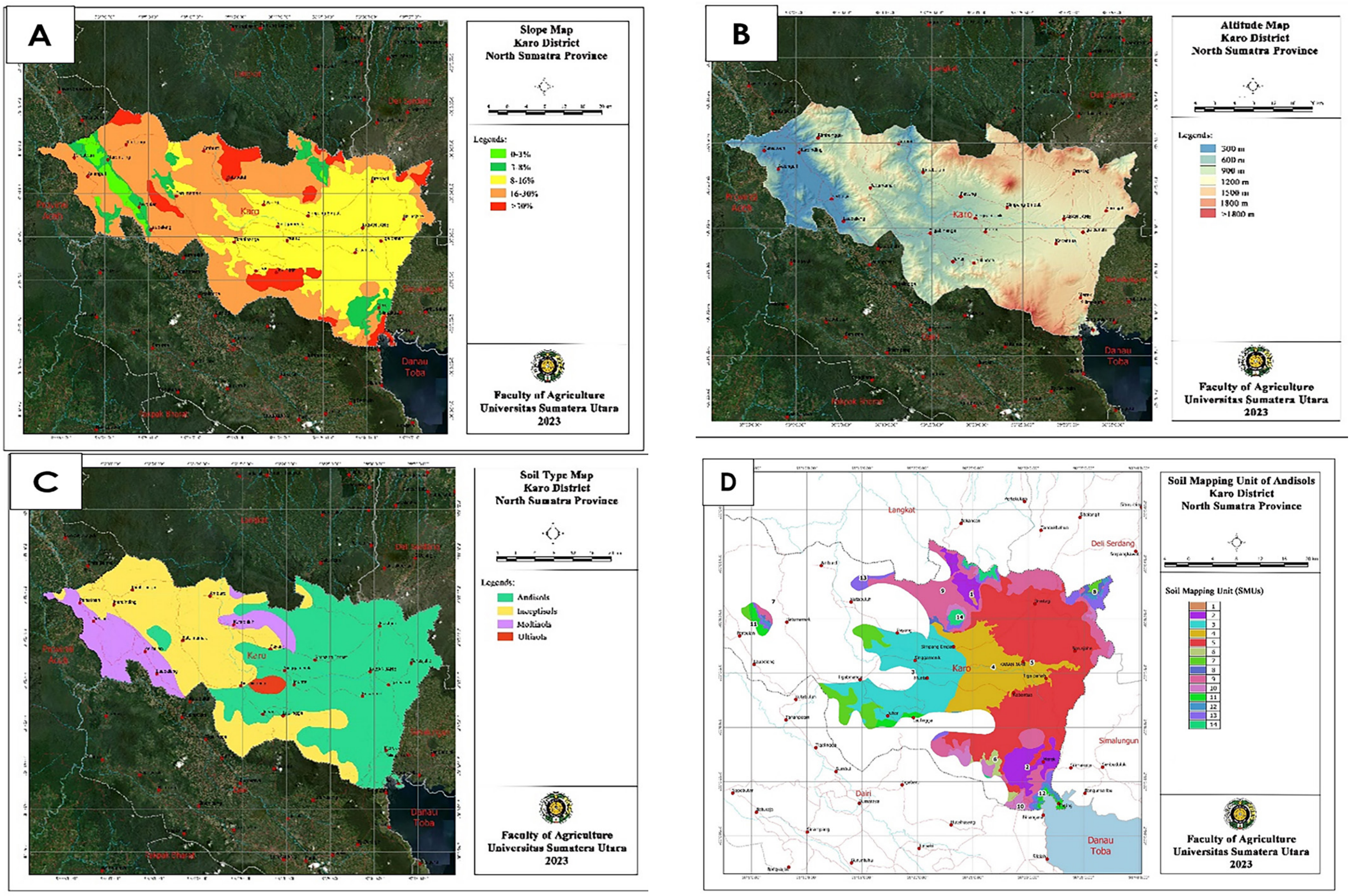

Figure 2. Maps of slope (A), altitude (B), soil type (C), and soil mapping units (D) overlaid in Karo District, North Sumatra, Indonesia.

Table 2. Coordinates and climatic data of each soil sampling site from 10 SMUs selected of potato crops in Karo District, North Sumatra, Indonesia.

SMUs selected	Samples	Coordinates		Climatic data	
		Latitude	Longitude	Air temperature (°C)	Air moisture (%)
1	1	3°11'33.305"N	98°24'43.383"E	18.2	80.8
	2	3°11'41.256"N	98°24'51.259"E	17.3	82.4
	3	3°12'23.156"N	98°24'55.621"E	16.8	85.1
2	1	3°12'23.921"N	98°24'14.713"E	18.5	80.5
	2	2°58'30.229"N	98°32'10.032"E	19.2	85.3
	3	3°12'07.046"N	98°24'17.442"E	17.2	82.3
3	1	3°09'08.759"N	98°26'25.489"E	22.2	71.5
	2	3°04'01.936"N	98°27'19.571"E	19.3	79.4
	3	3°07'47.661"N	98°25'01.230"E	18.8	75.1
4	1	3°06'22.636"N	98°31'20.704"E	18.4	83.9
	2	3°09'40.823"N	98°29' 4.584" E	18.2	83.5
	3	3°08'57.558"N	98°33'34.005"E	18.0	80.8
5	1	2°57'34.658"N	98°26'56.225"E	16.5	88.3
	2	2°55'41.233"N	98°27'23.418"E	15.9	90.1
	3	2°53'53.145"N	98°28'33.143"E	17.1	83.1
6	1	3°13'11.452"N	98°36'40.704"E	19.1	80.1
	2	3°12'13.262"N	98°34'47.137"E	21.2	79.1
	3	3°12'45.161"N	98°35'23.026"E	20.4	81.3
7	1	2°57'38.747"N	98°31'42.681"E	18.4	78.9
	2	3°10'58.876"N	98°25'37.871"E	17.7	80.1
	3	3°12'37.213"N	98°22'14.801"E	18.1	79.7
8	1	3°11'19.716"N	98°23'28.402"E	15.4	89.2
	2	2°56'58.025"N	98°25'53.814"E	16.2	90.5
	3	2°57'53.241"N	98°23'43.321"E	16.9	89.9
9	1	3°12'11.642"N	98°35'26.171"E	21.3	70.3
	2	2°59'31.424"N	98°30'30.809"E	20.7	75.2
	3	3°13'25.833"N	98°36'51.382"E	18.9	76.6
10	1	3°10'14.403"N	98°24'04.826"E	17.3	84.6
	2	3°14'22.645"N	98°26'46.313"E	15.5	90.8
	3	3°14'32.051"N	98°26'51.845"E	16.8	89.9

assessed using the HNO_3 method with Atomic Absorption Spectrophotometry (AAS). In addition, C:N ratio and Base Saturation (BS) were evaluated with calculation methods. Cation exchange capacity (CEC) and exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, Na^+) were measured using the Ammonium Acetate method at pH 7.

Data analysis and interpretation

According to Soil Research Institute (2009), the land characteristic data from each SMU were classified into very low, low, moderate, high, and very high. The relationship between soil physicochemical characteristics and potato yield was analyzed through Pearson correlation using IBM SPSS software.

Results and Discussion

Soil physicochemical characteristics

Physicochemical characteristics of andisols in the 10 SMUs selected for potato cropping in Karo District, North Sumatra, Indonesia, are shown in **Tables 3-4**. Soil moisture and water content varied, ranging from 61.97% to 84.03% and 14.47% to 23.53%, respectively. Furthermore, the dominant soil texture was sandy loam or moderately coarse, with a slope ranging from 1.20% to 37.23% as well as an altitude ranging between 1,088.33 to 1,627.33 meters above sea level (m A.S.L.). Chemical characteristics indicated that soil pH was acidic (4.63-4.99), with very low levels of BS and exchangeable-Ca. Soil C:N ratio was classified as very low to low, and exchangeable-Na was low. A total of four SMUs, namely 1, 5, 8, and 10 had low organic-C, CEC, and available-P were classified as moderate, while the other SMUs ranged from moderate to very high. Exchangeable-Mg was also classified as very low to moderate by 0.38-1.39 me/100 g. The values of exchangeable-K also varied from 0.37 to 0.89 me/100 g (low to high). In contrast, total-P and total-K were classified as very high and high to very high, with values ranging from 0.20% to 0.49% and 59.87 to 108.57 mg/100 g, respectively. The value of total-N ranged from moderate to high at 0.32-0.62%.

Potato yield (tons ha^{-1})

Potato yield per hectare in the 10 SMUs selected in Karo District, North Sumatra, Indonesia, is seen in **Figure 3**. Based on the results, potato yield ranged from 16.33 to 23.67 tons ha^{-1}. The highest yield was found in SMU 2, namely 23.67 tons ha^{-1}, while the lowest was recorded in SMU 5 by 16.33 tons ha^{-1}.

Correlation value

The correlation values between andisols' physicochemical characteristics and potato yield in the 10 SMUs selected are shown in **Table 5**. The CEC correlated positively and significantly (0.49**) with soil N-total. Similarly, total-K was significantly influenced by exchangeable-K with a correlation value of 0.38*. The characteristics of the C:N ratio and total-P also correlated positively and significantly with available-P with correlation values of 0.43* and 0.45*, respectively. The results indicated that potato productivity was significantly influenced by soil organic-C and C:N ratio, with correlation values of 0.44* and 0.43*, respectively. The relationship between organic-C and C:N ratio with potato yield in the 10 SMUs selected is depicted in **Figure 4**. Additionally, slope, altitude, water content, moisture, CEC, available-P, and total-K in andisols correlated positively with potato yield in Karo District, North Sumatra, Indonesia.

Figure 4 shows that organic-C and C:N ratios in andisols had a linear pattern concerning potato yield, with equations $y= 1.765x + 15.563$ and $y= 0.380x + 17.108$, respectively. This indicated that for each unit increase in soil organic-C and C:N ratio, potato yield increased by 1.765 and 0.380 tons ha^{-1}, respectively.

Effect of soil physic characteristics on available-P of andisols and potato yield

The primary issue with andisol soil lies in phosphate retention due to the presence of high levels of allophane minerals, rendering phosphorus unavailable to plants. This phosphate retention can be influenced by several soil physical characteristics. Based on the Table 5, only the silt and clay fractions correlated positively with available-P in andisols, although the effect was insignificant. It was caused by the 0-20 cm soil depth (topsoil), most minerals experienced weathering and increasing the silt and clay content. This result was supported by Arifin et al. (2022), the 0-17 cm soil depth or Ap-horizon had high mineral content, was easily weathered, and increased the clay content of andisols ranging from 27.14% to 40.36%. According to Nishigaki et al. (2021), the silt content correlated positively (0.233) with phosphate retention. Andriamananjara et al. (2016) also found that clay content and other soil parameters were closely related to available-P.

The loam and sandy loam soil textures in the 10 SMUs selected are highly suitable for supporting potato growth and yield. Similarly, slope, altitude, soil moisture and water content in this study strongly support potato tuber formation. These results were reinforced by the fact that slope, altitude, soil moisture and water content correlated positively with increased potato yield with values of 0.18; 0.23; 0.28; and 0.02, respectively, although the effects were insignificant (Table 5). The characteristics

Table 3. Physical characteristics of andisols at 10 SMUs selected in potato cropping in Karo District, North Sumatra, Indonesia.

SMUs selected	Soil moisture (%)	Soil water content (%)	Slope (%)	Altitude (m A.S.L.)	Texture fractions (%)			Soil textures
					Sand	Silt	Clay	
1	84.03	23.47	1.20	1354.67	65.52	31.88	2.60	Sandy loam
2	72.90	14.47	3.26	1376.67	57.61	36.31	6.08	Loam
3	67.43	22.23	9.51	1137.67	65.77	29.10	5.13	Sandy loam
4	61.97	20.30	9.69	1283.00	54.09	38.54	7.36	Loam
5	75.20	23.53	12.98	1627.33	66.62	29.55	3.83	Sandy loam
6	76.17	19.60	19.99	1088.33	78.69	17.55	3.76	Loamy sand
7	68.50	20.77	22.35	1328.67	67.04	29.15	3.81	Sandy loam
8	63.13	19.83	22.78	1612.67	64.29	33.04	2.67	Sandy loam
9	74.70	22.07	30.85	1100.00	70.36	25.90	3.74	Sandy loam
10	71.37	20.47	37.23	1596.00	63.73	32.35	3.92	Sandy loam

Table 4. Chemical characteristics of andisols at 10 SMUs selected in potato cropping in Karo District, North Sumatra, Indonesia.

SMUs selected	pH		Org-C (%)	C:N ratio	BS (%)	Exchangeable cations (me/100 g)			
	H_2O	KCl				K^+	Ca^{2+}	Mg^{2+}	Na^+
1	4.92 ± 0.06 (A)	3.83 ± 0.06	1.95 ± 0.52 (L)	4.71 ± 1.75 (VL)	17.05 ± 1.93 (VL)	0.64 ± 0.18 (H)	1.29 ± 0.15 (VL)	0.86 ± 0.45 (L)	0.33 ± 0.05 (L)
2	4.80 ± 0.16 (A)	3.98 ± 0.01	2.30 ± 0.40 (M)	7.96 ± 2.08 (L)	9.87 ± 0.34 (VL)	0.83 ± 0.30 (H)	0.85 ± 0.25 (VL)	0.74 ± 0.32 (L)	0.34 ± 0.07 (L)
3	4.71 ± 0.16 (A)	3.69 ± 0.19	2.43 ± 0.37 (M)	7.27 ± 4.53 (L)	6.17 ± 1.13 (VL)	0.37 ± 0.12 (L)	0.64 ± 0.18 (VL)	0.45 ± 0.18 (L)	0.20 ± 0.02 (L)
4	4.63 ± 0.19 (A)	3.87 ± 0.07	2.19 ± 0.33 (M)	7.03 ± 2.65 (L)	5.44 ± 1.02 (VL)	0.40 ± 0.18 (M)	0.52 ± 0.06 (VL)	0.38 ± 0.15 (VL)	0.20 ± 0.07 (L)
5	4.98 ± 0.06 (A)	3.53 ± 0.07	1.73 ± 0.55 (L)	5.09 ± 2.29 (L)	18.51 ± 7.78 (VL)	0.82 ± 0.14 (H)	1.05 ± 0.34 (VL)	1.26 ± 0.62 (M)	0.24 ± 0.03 (L)
6	4.80 ± 0.19 (A)	3.68 ± 0.12	3.05 ± 0.61 (H)	7.61 ± 1.56 (L)	6.05 ± 1.33 (VL)	0.63 ± 0.08 (H)	0.77 ± 0.13 (VL)	0.66 ± 0.18 (L)	0.23 ± 0.04 (L)
7	4.84 ± 0.08(A)	3.83 ± 0.06	2.33 ± 0.47 (M)	5.77 ± 0.29 (L)	8.56 ± 1.52 (VL)	0.89 ± 0.06 (H)	0.96 ± 0.23 (VL)	0.84 ± 0.22 (L)	0.22 ± 0.03 (L)
8	4.93 ± 0.07 (A)	3.66 ± 0.10	1.86 ± 0.44 (L)	5.20 ± 1.32 (L)	18.00 ± 9.65 (VL)	0.67 ± 0.20 (H)	1.59 ± 0.71 (VL)	1.10 ± 0.56 (M)	0.25 ± 0.02 (L)
9	4.82 ± 0.13 (A)	3.55 ± 0.04	3.08 ± 0.27 (H)	9.68 ± 2.68 (L)	5.83 ± 0.58 (VL)	0.51 ± 0.11 (M)	0.38 ± 0.08 (VL)	0.66 ± 0.34 (L)	0.22 ± 0.01 (L)
10	4.99 ± 0.07(A)	3.63 ± 0.11	1.75 ± 0.54 (L)	4.32 ± 1.28 (VL)	15.61 ± 3.00(VL)	0.82 ± 0.13 (H)	1.12 ± 0.43 (VL)	1.39 ± 0.57 (M)	0.20 ± 0.02 (L)

SMUs selected	CEC (me/100 g)	Total-N (%)	Total-P (%)	Available-P (mg/kg)	Total-K (mg/100 g)
1	19.85 ± 7.31 (M)	0.46 ± 0.11 (M)	0.47 ± 0.10 (VH)	10.78 ± 1.84 (M)	71.17 ± 41.09 (VH)
2	28.03 ± 9.07 (H)	0.32 ± 0.09 (M)	0.42 ± 0.13 (VH)	23.11 ± 6.68 (VH)	89.33 ± 51.58 (VH)
3	29.63 ± 9.25 (H)	0.62 ± 0.23 (H)	0.20 ± 0.03 (VH)	15.06 ± 3.94 (VH)	59.87 ± 13.52 (H)
4	29.94 ± 8.25 (H)	0.37 ± 0.08 (M)	0.46 ± 0.10 (VH)	18.27 ± 2.21 (VH)	86.60 ± 12.30 (VH)
5	22.71 ± 5.53 (M)	0.41 ± 0.04(M)	0.43 ± 0.14 (VH)	10.82 ± 1.34 (M)	77.27 ± 2.71 (VH)
6	39.62 ± 4.46 (H)	0.41 ± 0.04 (M)	0.49 ± 0.20 (VH)	18.32 ± 8.84 (VH)	90.37 ± 2.43 (VH)
7	35.92 ± 6.66 (H)	0.40 ± 0.07 (M)	0.36 ± 0.07 (VH)	12.41 ± 4.07 (H)	108.57 ± 25.11 (VH)
8	23.68 ± 4.92 (M)	0.36 ± 0.04 (M)	0.27 ± 0.07 (VH)	9.10 ± 1.45 (M)	90.13 ± 25.32 (VH)
9	30.00 ± 4.14 (H)	0.35 ± 0.05 (M)	0.38 ± 0.03 (VH)	15.06 ± 3.73 (VH)	84.73 ± 21.67 (VH)
10	22.72 ± 1.33 (M)	0.40 ± 0.03 (M)	0.45 ± 0.10 (VH)	10.31 ± 0.99 (M)	87.83 ± 17.44 (VH)

Note: the average followed by the symbol ± indicates the standard error. The criteria for H_2O-pH (acid/A= 4.5-5.5); organic-C (low/L= 1-2%; moderate/M= 2.01-3%; high/H= 3.01-5%); C:N ratio (very low/VL< 5; low/L= 5-10); base saturation/BS (very low/VL< 20%); CEC (moderate/M= 17-24 me/100 g; high/H= 25-40 me/100 g); exchangeable-K (low/L= 0.1-0.4 me/100 g; moderate/M= 0.4-0.59 me/100 g; high/H= 0.6-1 me/100 g); exchangeable-Ca (very low/VL< 2 me/100 g); exchangeable-Mg (very low/VL< 0.4 me/100 g; low/L= 0.4-1 me/100 g; moderate/M= 1.1-2 me/100 g); exchangeable-Na (low/L= 0.1-0.3 me/100 g); total-N (moderate/M= 0.21-0.5%; high/H= 0.51-0.75%); total-P (very high/VH> 0.06%); available-P (moderate/M= 8-10.99 mg/kg; high/H= 11-15 mg/kg; very high/VH> 15 mg/kg); and total-K (high/H= 41-60 mg/100 g; very high/VH> 60 mg/100 g). The criteria for each of these soil chemical characteristics refer to the Soil Research Institute (2009).

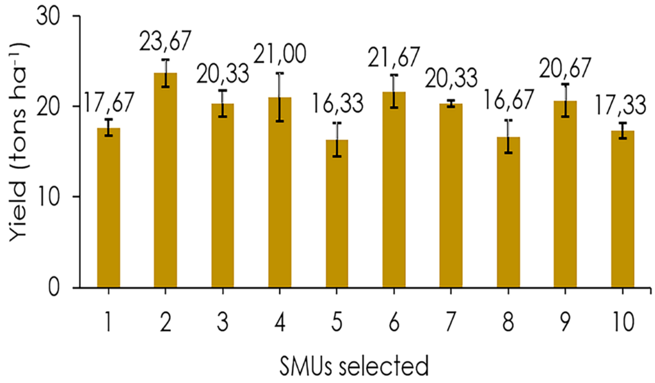

Figure 3. Potato yield for 10 SMUs selected of potato crops in Karo District, North Sumatra, Indonesia. The vertical line represents the standard error.

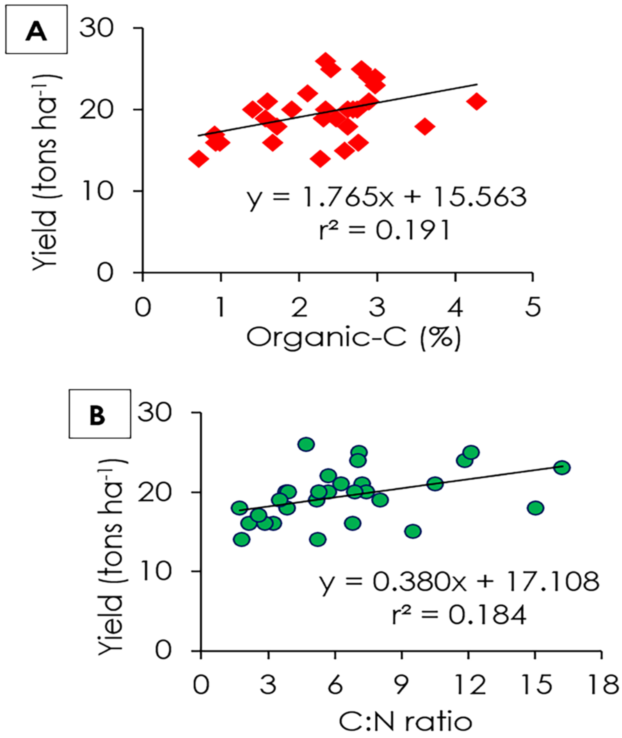

Figure 4. Relationship of C-organic (A) and C:N ratio (B) in andisols to potato yield at 10 SMUs selected in Karo District, North Sumatra, Indonesia.

of soil moisture and water content were closely related to plant metabolism, specifically root development in nutrient and water absorption, thereby affecting biomass and potato tuber formation. According to Hsiao & Jackson (1999) excessive soil moisture can disrupt plant root development due to oxygen deficiency, leading to inadequate nutrient uptake. An et al. (2008) added that soil moisture deficiency (water stress) leads to leaf shedding and inhibits leaf expansion as well as crop production. Abd El-Latif et al. (2011) recorded potato biomass and yield increase by 29.25-62.01% and 28.41-49.68%, respectively at soil moisture levels of 60-80% compared to soil moisture at 40%. Soil texture is also closely related to plant root development. According to Gil et al. (2012) and Chaudhari et al. (2013), soil texture can affect soil density, thereby disrupting root development in nutrient and water uptake. Djaenudin et al. (2011) also stated that soil texture categorized as moderately coarse and medium (sandy loam and loam) were highly suitable for supporting potato growth. Meanwhile, slope and altitude are related to temperature and rainfall, which affect the soil organic matter decomposition process, increasing nutrient availability (Ping et al., 2013; Saeed et al., 2014; Van Beusekom et al., 2015). Hu et al. (2018) also found that altitude and slope significantly influenced soil organic carbon.

In general, physical characteristics such as slope, altitude, soil moisture and water content have a significant impact on soil chemical properties, thereby influencing potato yield. Zare et al. (2019) reported that slope and altitude can increase potato yield by 22-36%. Nyawade et al. (2019) also found that soil water content significantly influenced potato yield. According to Alva et al. (2012) and Liang et al. (2019), soil moisture is a critical factor affecting harvest yields and potato tuber quality.

Effect of soil chemical characteristics on available-P of andisols and potato yield

The soil chemical analysis results showed that the available-P in the 10 SMUs selected was predominantly very high. There were four SMUs, namely SMU 1, 5, 8, and 10, that had lower available-P, although the values were classified as moderate compared to others (Table 4). The low availability of phosphorus in 4 SMUs was closely related to soil pH, organic-C, C:N ratio, CEC, and total-P. These results were reinforced by Table 5, showing that available-P correlated negatively with soil pH (-0.64^{**}), but positively with soil organic-C, C:N ratio, CEC, and total-P with correlation values of 0.29; 0.43^{*}; 0.16; and 0.45^{*}, respectively. Soil pH in 1, 5, 8, and 10 SMUs was greater than 4.9 impacting the formation of allophane. This result was supported by Shoji et al. (1993) stating that pH 4.9 was identified as a critical value for allophane formation. Higher pH greater than 4.9 will lead to allophane formation. Parfitt & Kimble (1989) added that optimal allophane formation occurs at pH levels ranging from 5 to 7. Hashimoto et al. (2012); Anda & Dahlgren (2020) reported that soil pH correlated negatively with phosphate retention due to Al-P and Fe-P adsorption on andisols. In contrast, organic-C and CEC in SMU 1, 5, 8, and 10 were lower compared to SMU others. This could be a contributing factor to the lower availability of phosphorus in these SMUs. Correspondingly, Yan et al. (2013); Yang

Table 5. Correlation between andisol physicochemical properties at 10 SMUs selected on the potato yield in Karo District, North Sumatra, Indonesia.

No	Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	Sand	1	-0.98**	-0.41*	0.16	-0.23	0.11	0.11	0.26	-0.05	-0.38*	0.09	0.40*	0.36	-0.04	0.39*	0.06	0.45*	0.17	-0.35	-0.07	-0.13
2	Silt		1	0.22	-0.14	0.28	-0.08	-0.06	-0.18	0.04	0.34	-0.06	-0.37*	-0.32	0.10	-0.37*	-0.05	-0.43*	-0.15	0.31	0.08	0.08
3	Clay			1	-0.15	-0.19	-0.16	-0.25	-0.43*	0.04	0.29	-0.17	-0.22	-0.29	-0.26	-0.21	-0.07	-0.22	-0.15	0.29	-0.03	0.30
4	Slope				1	0.13	0.08	-0.13	0.17	0.10	0.03	0.02	0.05	0.11	0.02	0.20	-0.44*	-0.17	-0.05	-0.22	0.16	0.18
5	Altitude					1	0.04	0.01	0.41*	-0.46*	-0.34	0.56**	-0.34	0.33	0.51**	0.35	0.09	-0.12	-0.01	-0.33	0.01	0.23
6	SWC						1	0.35	0.18	-0.02	-0.08	0.24	0.02	0.09	0.14	0.28	-0.09	0.13	0.30	-0.14	-0.07	0.28
7	Soil moisture							1	0.39*	0.17	-0.06	0.06	0.10	0.05	0.13	0.04	0.42*	0.11	0.12	-0.16	-0.05	0.02
8	Soil pH								1	-0.22	-0.46**	0.17	0.14	0.39*	0.26	0.35	0.16	0.18	-0.10	-0.64**	-0.18	-0.28
9	Org-C									1	0.73**	-0.48**	0.17	-0.34	-0.19	-0.45*	-0.25	-0.10	-0.17	0.29	-0.03	0.44*
10	C:N										1	-0.35	-0.27	-0.47**	-0.30	-0.51**	-0.30	-0.61**	-0.27	0.43*	0.18	0.43*
11	BS											1	-0.56**	0.46**	0.61**	0.70**	0.19	-0.10	0.23	-0.31	0.09	-0.43*
12	CEC												1	0.22	-0.10	-0.01	-0.06	0.49**	0.28	0.16	-0.01	0.16
13	Exch-K													1	0.40*	0.71**	0.10	0.09	0.45*	-0.21	0.38*	-0.07
14	Exch-Ca														1	0.40*	0.15	0.11	0.05	-0.34	0.09	-0.26
15	Exch-Mg															1	0.20	0.12	0.45*	-0.28	0.11	-0.30
16	Exch-Na																1	0.10	0.23	-0.01	-0.10	-0.09
17	Total-N																	1	0.07	-0.23	-0.41*	-0.22
18	Total-P																		1	0.45*	0.13	-0.15
19	Available-P																			1	0.03	0.30
20	Total-K																				1	0.27
21	Yield																					1

Note: * and ** indicated correlation is significant at the 0.05 and 0.01 level (2-tailed). n= 30 samples. SWC= soil water content; BS= base saturation; CEC= cation exchange capacity

et al. (2019); Maritasari et al. (2022) suggested that the addition of organic matter could increase available phosphorus through organic acids such as humic and fulvic acids, by binding Al and Fe in andisols. Smalberger et al. (2006) also explained that organic-C played a role in increasing soil CEC, causing exchangeable-Ca to bind to colloids and phosphate, thereby making phosphorus available for plant uptake. In this study, exchangeable-Ca in 1, 5, 8, and 10 SMUs were higher compared to others (Table 4). Anda & Dahlgren (2020) added that a low C:N ratio indicates a high level of humification, forming Al-humus complexes capable of inhibiting allophane formation in andisols.

Among the soil chemical characteristics, organic-C and C:N ratios demonstrated a significant and positive correlation with increasing potato yield in the 10 SMUs selected (Table 5 and Figure 4). Additionally, parameters such as CEC, available-P, and total-K in the andisol also showed a positive correlation with potato yield. Soil organic-C and C:N ratios have a significant influence on increasing CEC, available-P, and total-K, thereby affecting nutrient uptake during growth and tuber production. According to Korkmaz et al. (2015) soil organic matter positively correlated with several macro-micro nutrient levels in potato shoots. Tarigan & Hanum (2019) also explained that available phosphorus in andisols correlated positively (0.153) with potato yield. Similarly, Xing et al. (2020) found that soil organic-C, available-P, and available-K impacted potato yield.

As a cover, soil physical characteristics including slope, altitude, soil moisture, soil water content, and soil texture predominantly supported potato yield, although the correlation was relatively weak. However, soil chemical characteristics were less optimal in supporting potato yield. Among the soil chemical characteristics, only organic-C and C:N ratios showed a significant and positive correlation with potato yield. Some alternatives to improve the chemical properties of andisols include the application of humic and fulvic acid, silicate, potential phosphate-solubilizing microbes, and hydroxyapatite nanoparticles. These additives can enhance nutrient uptake, specifically available phosphorus, thereby resulting in optimal tuber production.

Conclusions

The silt and clay fractions were identified to have a positive relationship with the availability of phosphorus in andisols compared to other physical properties. All soil physical characteristics in this study supported potato yield, except for the sand fraction. A total of 4 from 10 SMUs selected namely 1, 5, 8, and 10 had lower available phosphorus and were closely related to soil pH, organic-C, C:N ratio, CEC, and total-P. The rise in organic-C and C:N ratio contributed to increasing potato yield by 1.765 and 0.380 tons ha^{-1} in the 10 SMUs selected in Karo District, North Sumatra, Indonesia.

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