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RESEARCH ARTICLE Agricultural Science Digest

Soil Fractions Affect on Soil Organic Carbon Stock in the Coastal Land of Aceh Utara Regency, Indonesia

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10.18805/ag.DF-564

ABSTRACT

Background: Soil organic carbon stocks (SOCs) play a critical role in supporting soil quality and ecosystem functions. Information on SOCs content in coastal lands is scanty and the types of clay minerals and soil fraction size that affect SOCs are still debated. We evaluated the SOCs content and identified the mineral type and soil fraction affecting the SOCs on coastal land.

Methods: Soil samples were collected from each layer of nine different soil profiles in three subdistricts: Seunuddon (SD), Lapang (LP) and Dewantara (DT) in Aceh Utara Regency of Indonesia. The soil profiles were taken from different distances (300, 900 and 1500 m from the shoreline-d.f.s).

Result: The results revealed that SOCs possessed by each soil layer of coastal land in Aceh Utara varied between 0.64 to 43.45 MgC ha^{-1}. The highest to lowest average total of SOCs content for the location is SD>DT>LP, while for the position, the distance to the shoreline is 900 m>1500 m>300 m. Clay minerals such as labradorite, smectite, vermiculite and chlorite positively increase the SOCs content. Very fine sand is a size of the soil fraction that affects the increase in the levels of SOCs in coastal land.

Key words: Clay minerals, Shoreline, Soil fraction size, Soil organic carbon, Soil properties.

INTRODUCTION

The dynamics of SOCs are a major concern, as this component is a vital indicator for soil health and climate change (Manna *et al*., 2013) SOCs significantly influenced the chemical and biological properties of the soil and the emission of CO_2 and methane to the atmosphere (Chahal and Singh, 2021). The loss or reduction of SOC led to a decrease in soil quality and escalating global warming (Yigini and Panagos, 2016), threatening global food security and affecting sustainable development in a country (Adhikari *et al*., 2019). Soil is the largest reservoir of organic carbon, with the total carbon stored in the soil depth of 100 cm ranging from 899-2400 PgC. SOCs can vary depending on soil type and location and are affected by texture, climate, vegetation, topography and clay minerals (Jiao *et al*., 2020; Seboko *et al*., 2021).

SOCs levels may differ in different land use types and locations, including coastal areas. Coastal land is one of the SOC reservoirs too, contributing to the global carbon cycle Das *et al.* (2015), but information on the dynamics and content of SOCs in coastal land is scanty. The SOCs levels in various types of land uses other than coastal lands have been widely reported, including paddy fields Liu *et al.* (2021), cropland Hounkpatin *et al.* (2018), urban gardening Canedoli *et al.* (2020), forests Merabtene *et al.* (2021), at different cropping systems (Chakrabarti *et al*., 2019; Nthebere *et al*., 2022). Anokye *et al.* (2021) also reported SOCs content in palm oil plantations and farmland. Then, SOCs in natural vegetations Zhu *et al.* (2021), saltmarshes and tidal flats Byun *et al.* (2019) and in sloping mangrove ecosystems (Sasmito *et al*., 2020). Fu *et al.* (2021) also reported SOCs in mangrove swamps, saltmarshes and seaweed. According to Liu *et al.* (2021) that mangrove ecosystems in different depths (0-30 cm and 0-100 cm) exhibited different amounts of SOCs and indicated different SOCs levels according to soil depth.

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How to cite this article: Khusrizal, Nasruddin, Yusra, Hidayat, A. and Rusdi, M. (2023). Soil Fractions Affect on Soil Organic Carbon Stock in the Coastal Land of Aceh Utara Regency, Indonesia. Agricultural Science Digest. DOI: 10.18805/ag.DF-564.

Submitted: 24-06-2023 **Accepted:** 04-10-2023 **Online:** 19-10-2023

The clay minerals and soil textures play an important role in affecting SOCs (Seboko *et al*., 2021; Singh *et al*., 2018). Clay minerals have different surface charges, so they have different capacities for protecting and increasing SOCs (Sarkar *et al*., 2018), where clay minerals 2:1 have a higher capability for increasing SOCs compared to clay minerals 1:1 (Matus *et al*., 2016). A study by Zeraatpishe dan Khormali (2012) found that illite and chlorite were responsible for the increase in SOCs. Another study conducted bySingh *et al.* (2018) Singh *et al.* (2017) indicated that montmorillonite and vermiculite stabilize SOC content. Apart from the minerals mentioned above, it is also possible for other clay minerals to affect SOCs as long as they have a charge and surface area (Tan, 2010).

On the other hand, Jindaluang *et al.* (2013) stated that soil texture and fraction contributed to SOC stabilization. However, there are several perspectives on this. Some studies claim that soil fraction plays a significant role in SOCs (Schweizer *et al*., 2021; Zhong *et al*., 2018). Research by Marques *et al.* (2015) confirmed that SOCs in fine soil are higher compared to coarse soil fractions. Nonetheless, Merabtene *et al.* (2021) found that the coarse soil fractions also positively contributed to the increase in SOCs. This study aims to investigate the actual mineral types and soil fraction sizes that control the SOCs of coastal land.

MATERIALS AND METHODS

Research site

This study was conducted in coastal lands in 3 districts: Seunuddon (SD), Lapang (LP) and Dewantara (DT) in Aceh Utara, Aceh Province, Indonesia (Fig 1), from June to October 2022. SD is located in the east, LP in the middle and DT in the west of Aceh Utara Regency. Geographically, Aceh Utara Regency is located at 96°52′00″-97°31′00″ east longitude and 04°46′00″-05°00′40″ north latitude.

In this research, we used data on annual average climate (2007-2021), rainfall, temperature and humidity obtained from the Indonesian Agency for Meteorology, Climatology and Geophysics in Aceh Utara. In the past 15 years, the city recorded 1,488.75 mm/year, an average annual temperature of 27.7°C, where maximum and minimum temperatures were 32.9 and 22.6°C and an annual average humidity of 83%.

Geologically, this research site possesses alluvial deposits (Qh) and Idi Qpi patterns. The formation of Qh (holocene) is sandy and fluviatil sediment, while Qpi (pleistocene) is in the form of compressed gravel, sand, limestone and clay, which is dominantly found in Aceh Utara Seunuddon, Lapang and Dewantara subdistricts. Nonetheless, the Qpi pattern can only be found in narrower areas where the soil types are Entisols, Inceptisols and Ultisols, with Entisols and Inceptisols being dominant and often used for swamps, shrubs, coconut plantations, paddy fields, ponds and settlements(Keats *et al*., 1981; Puslittanak, 1991).

Data collection and parameters for soil properties

The soil samples were obtained from a representative soil profile, whose position is determined by its distance from the shoreline (d.f.s.). The distance from the shoreline was divided into three groups: short (300 m), middle (900 m) and long (1500 m). Fig 2a, 2b and 2c displays the placement of each soil profile in relation to the distance from the shoreline at each location. One typical soil profile with a width of 0.8 m, a length of 0.8 m and a depth of 0.8 m is created at each place along the distance. Each profile possessed four layers of the same thickness, 20 cm.

There are a total of 36 layers (36 soil samples) obtained from three districts. From each stratum, undisturbed soil aggregates were obtained using a sample ring (diameter 53 mm and volume 100 cm^3) and cut using a knife, while disturbed soil samples were collected using a bayonet (1.5 kg of soil samples put into a plastic bag). The undisturbed soil aggregates were used in bulk density analysis (g cm^{-3}) using the sample ring kit model C53 (Grossman and Reinsch, 2002), The disturbed soil aggregates have to be air-dried before sieving (10 mesh). This soil sample has been used to determine the clay mineral types and composition using the qualitative method of X-ray diffraction (Hughes *et al*., 1994), to investigate soil fraction (%) (very coarse sand, coarse sand, medium sand, fine sand, very fine sand, silt, clay) by the pipetting method (Olmstead *et al*., 1930) and to assess organic-C (%) by the Walkley and Black method (Black *et al*., 1965).

Soil organic carbon stock calculation and data analysis

SOCs were calculated using the formula by Yigini dan Panagos (2016), where,

$$\text{SOCs (MgC ha}^{-1}) = \text{Organic-C (\%)} \times \text{bulk density (g cm}^{-3}) \times \text{thickness of the horizon (cm)}.$$

This assessment is applied to each layer of the soil profile obtained. The total of SOCs is obtained by adding up the SOCs values from each layer (layers I to IV). The means of SOCs obtained from each location and distance were also calculated by including the total of SOCs and separating them into three. It applied to the total SOCs obtained from the distance of the coastal line as well.

The data from clay mineral analysis acquired from all soil profiles is categorized as qualitative data. Therefore, the data needs to be adjusted to be quantitative data to be used and analyzed to quantify its relationship to SOCs by applying scoring functions: 5 (predominant), 4 (dominant), 3 (moderate), 2 (low) and 1 (very low). The data on soil fraction and other soil properties obtained from three locations were involved in this quantitative analysis.

Statistical analysis

Correlation analysis Spearman and multiple linear regression analyses were performed to assess the correlation of clay minerals and soil fractions to SOCs. This correlation matrix analysis helped investigate the relationship between clay minerals and soil fractions on SOCs, while the multiple linear regression analysis helped identify the effect of clay minerals and soil fraction size on SOCs.

RESULTS AND DISCUSSION

Bulk density and soil fraction

Bulk density (BD) in the study area ranges from 0.79 to 1.90 g cm^{-3}. Spatially, the lowest mean of (BD) was found in the soil within 900 m d.f.s. (1.27 g cm^{-3}), followed by soil in 1500 m and 300 m d.f.s. (1.52 and 1.64 g cm^{-3}). Vertically, the highest BD (1.65 g cm^{-3}) was recorded at the depth of 40-60 cm, with the lowest (1.21 g cm^{-3}) at the depth 0-20 cm. The distribution of soil bulk density values is linked to soil fraction and soil organic matter. Soils with higher organic-C and a finer soil fraction tend to have lower bulk density (Azuka and Idu, 2022; Hossain *et al*., 2015). The soil fraction of the study area is dominated by fine sand (21.2-71.8%), followed by medium sand (3.7-44.4%), silt (1.0-30.9%) and very coarse sand (0.1-4.3%). The value of fine sand in SD and LP increased with further distance from the shoreline. In contrast, at DT, its value decreased with further distance from the shoreline. The parent materials of this coastal land, such as sandstone, silt and clay rocks, influenced and dominated the very fine sand in this area. The parent materials generate a finer sand fraction as well as silt. This finding is in line with Szymański *et al.* (2019), where he stated that parent materials such as silt and clay rocks will result in a finer soil fraction.

Soil organic carbon and cation exchange capacity

The highest average of organic-C (0.07-1.05%) was found at 900 d.f.s. and vertically decreased with soil depth. We assumed that organic matter influenced the high content of organic-C at 900 d.f.s., which was contributed by higher vegetation cover where this area was utilized as coconut

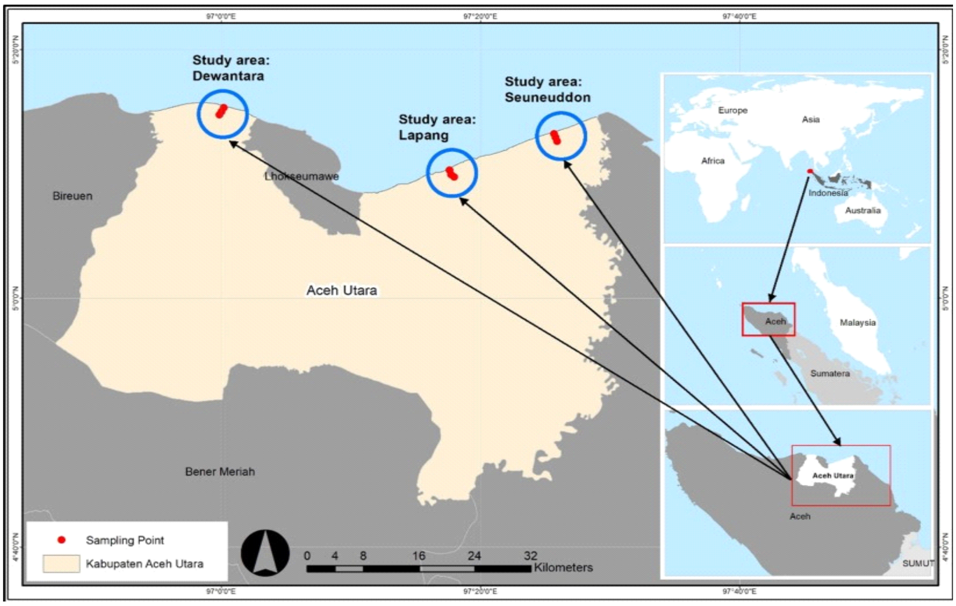

Fig 1: Location of the study area.

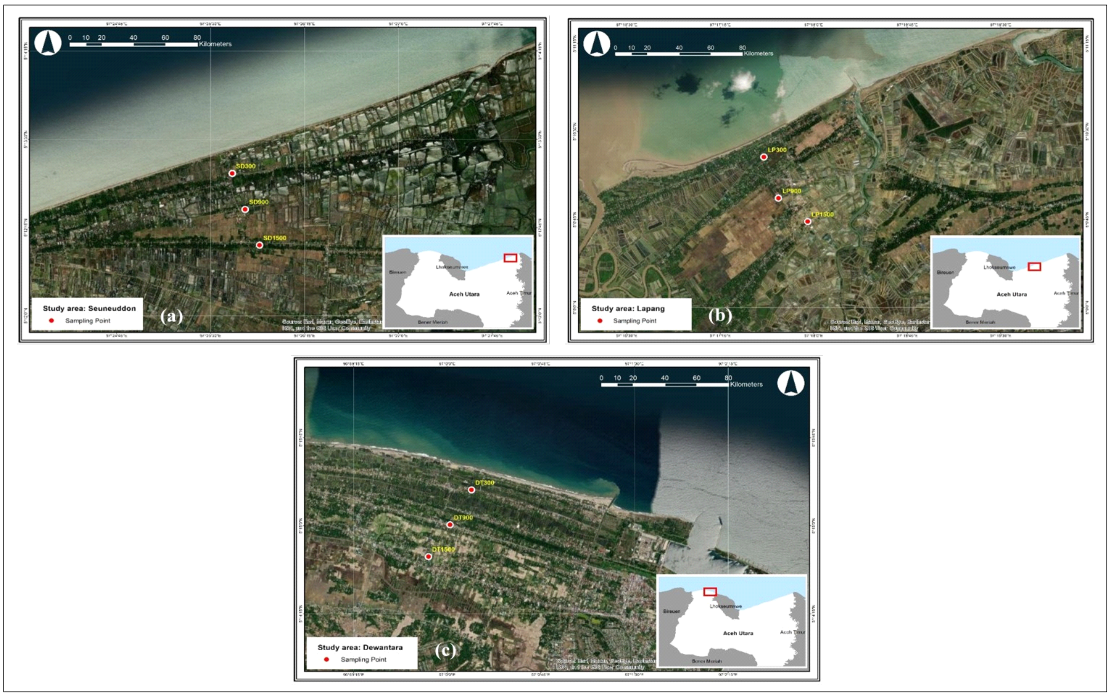

Fig 2: Soil profile position according to distance from the shoreline SD (a), LP (b), and DT (c).

plantations and shrubs. Kadiri *et al.* (2021) have also explained that these two types of land use trigger a higher amount of organic matter compared to undeveloped land. We also observed that the CEC in this area was low (5.72-9.66 $cmol_c$ kg^{-1}) and decreased with the soil depth. The higher CEC (9.66 $cmol_c$ kg^{-1}) was found at 900 d.f.s., followed by 1500 m and 300 m d.f.s. Low CEC is caused by low organic matter and smectite (type 2:1). These colloids were higher at 900 d.f.s., compared to 300 m and 1500 m d.f.s. Organic matter has a very high CEC (Saidian *et al*., 2016).

Clay mineral composition

In this study area, we found nine mineral clays: kaolinite, vermiculite, illite, chlorite, goethite, quartz, labradorite, smectite and dolomite. These minerals varied in number, from low to moderate. However, kaolinite dominates with a moderate number, followed by illite (moderate-low), chlorite (moderate-low), quartz (low-very low) and vermiculite (low-very low). These former minerals can be found in most soils, while the latter, which are smectite, goethite and dolomite, are very low and can be found in a few soil profiles. For instance, we discovered very few labradorite (at the depth 0-20 cm) in SD at 1500 m d.f.s and in DT (at the depth 0-20 and 20-40 cm) at 300 m d.f.s. The dominance of kaolinite and low smectite is attributed to parent materials formed in this land. Kaolinite and smectite are the parent materials of kaolin (Supandi *et al*., 2019). In addition, the modification of hydrothermal solutions in andesite rocks can result in the formation of kaolinite (Dill, 2016). The occurrence of labradorite in coastal lands is reasonable considering that this mineral may be found worldwide and is formed by igneous or metamorphic rocks (Meyer and Montague, 1989).

Soil organic carbon stock

Soil organic carbon stocks on coastal lands of varied depth and shoreline are described in Fig 3 (a, b and c). Those figures illustrated that the SOCs varied with the soil depth (between 0.64 to 43.45 MgC ha^{-1}). These results showed that in Aceh Utara, SOCs in coastal land were lower compared to coastal mud and mangrove ecosystems (Casey *et al*., 1989; Sasmito *et al*., 2020), as well as tidal marshes and coastal wetlands (Byun *et al*., 2019). The average of SOCs in those 3 locations was between 34.18-59.20 MgC ha^{-1}, with the highest (59.20 MgC ha^{-1}) recorded in SD, followed by DT (39.59 MgC ha^{-1}) and LP (34.18 MgC ha^{-1}) (Fig 4a). Higher total SOCs in SD is related to higher soil organic matter compared to DT and LP. High soil organic matter increases SOCs retention (Chahal and Singh, 2021). The average of SOCs from shoreline ranged from 34.94-50.42 MgC ha^{-1} with the highest total average was 50.42 MgC ha^{-1} at 900 m d.f.s and the lowest of 34.94 MgC ha^{-1} at 300 m d.f.s (Fig 4b). SOCs were determined by organic-C distribution, fine sand fraction and bulk density (Urgessa and Ferede, 2023). Soils with higher organic-C and fine sand fractions possess higher SOCs, as demonstrated by soils at 900 m d.f.s.

Relationship between clay minerals and soil fraction with soil organic carbon stock

The correlation coefficient between clay minerals and soil fraction was given in Table 1, with the coefficient value in

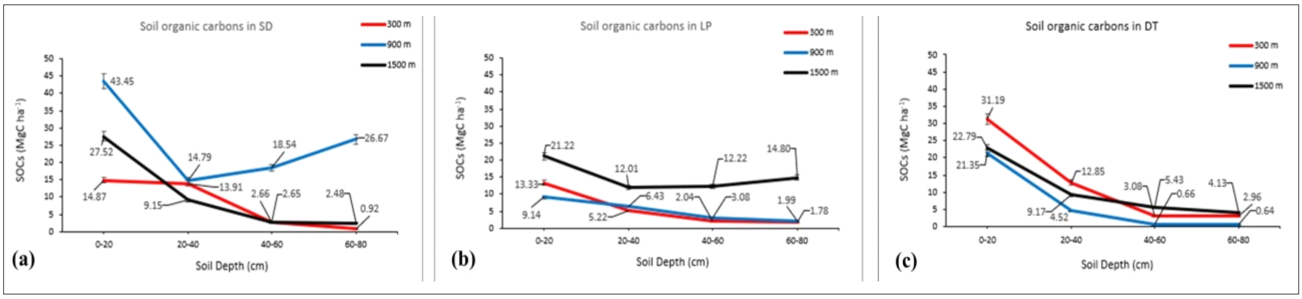

Fig 3: Content of SOCs according soil depth and distance from shoreline, SD (a), LP (b), and DT (c).

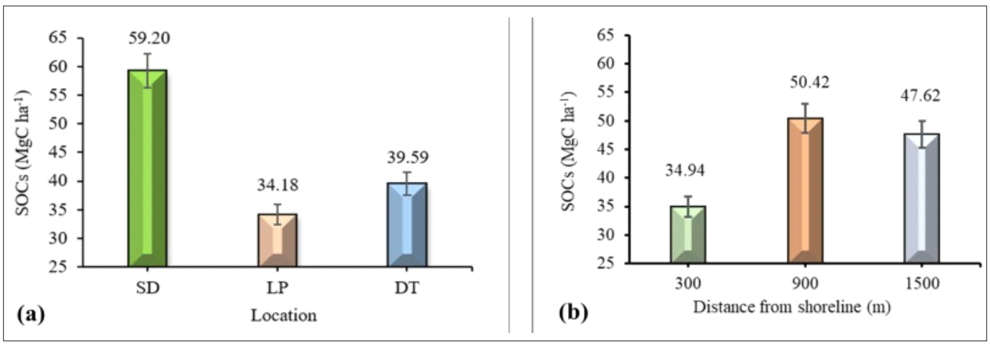

Fig 4: Average of SOCs content based on location (a) distance from shoreline (b).

Table 1: Spearman's correlation between clay minerals and soil fraction on SOCs.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	Y
X1	1																
X2	0.36[b]	1															
X3	-0.03	0.10	1														
X4	0.14	0.05	0.49[a]	1													
X5	0.32	0.39[b]	0.60[a]	0.47[a]	1												
X6	-0.14	-0.12	0.05	0.49[a]	0.06	1											
X7	0.29	0.45[a]	0.04	-0.15	0.13	-0.09	1										
X8	0.42[b]	0.46[a]	-0.02	0.13	0.23	0.10	0.14	1									
X9	0.04	-0.01	0.16	0.40[b]	0.36[b]	0.27	0.15	0.10	1								
X10	-0.02	-0.15	-0.64[a]	-0.69[a]	-0.38[b]	-0.44[a]	-0.10	-0.24	-0.37[b]	1							
X11	-0.06	-0.25	-0.46[a]	-0.58[a]	-0.22	-0.45[a]	-0.04	-0.38[b]	-0.25	0.84[a]	1						
X12	-0.06	-0.36[b]	0.05	-0.34[b]	0.12	-0.36[b]	0.10	-0.48[a]	0.06	0.40[b]	0.73[a]	1					
X13	0.09	0.13	0.08	0.55	0.01	0.49[a]	-0.06	0.34[b]	0.09	-0.62[a]	-0.72[a]	-0.77[a]	1				
X14	-0.06	0.07	-0.05	-0.62[a]	-0.26	-0.48[a]	0.22	0.04	-0.14	0.25	0.06	0.07	-0.46[a]	1			
X15	-0.14	0.25	0.23	-0.22	-0.11	-0.10	0.20	0.16	-0.04	-0.11	-0.31	-0.17	-0.29	0.69	1		
X16	0.07	0.23	0.00	0.17	0.07	0.17	-0.26	0.33	-0.07	-0.18	-0.51[a]	-0.67[a]	0.24	0.20	0.37[b]	1	
Y	0.19	0.44[a]	0.20	0.19	0.26	0.10	0.48[a]	0.41[b]	0.11	-0.24	-0.24	-0.18	0.15	0.08	0.04	0.12	1

Note: X1=Kaolinite; X2=Vermiculite; X3=Illite; X4=Chlorite; X5=Goethite; X6=Quartz; X7=Labradorite; X8=Smectite; X9=Dolomite; X10=Very coarse sand; X11=Coarse sand; X2=Medium sand; X13=Fine sand; X14=Very fine sand; X15=Silt; X16=Clay; Y=Soil organic carbon stocks.

a=Correlation is signifivant at the 0.01 level (2-tailed); b = Correlation is signifivant at the 0.05 level (2-tailed).

Table 2: Regression analysis of clay minerals and soil fraction with soil organic carbon stocks (SOCs).

Variable	Slope	Standard error	t-ratio	*p*<.05	
Kaolinite	-8.120	3.935	-2.064	.053	
Vermiculite	8.216	3.682	2.231	.038	
Illite	8.268	4.739	1.749	.096	
Chlorite	8.248	3.720	2.217	.039	
Goethite	-12.755	6.089	-2.095	.050	Constant = -65.098
Quartz	6.208	3.554	1.747	.097	R^2 = .705
Labradorite	15.811	5.491	2.880	.010	F-ratio = 2.836
Smectite	9.428	2.952	3.194	.005	SEE = 7.477
Dolomite	-1.465	2.776	-.528	.604	n = 36
Very coarse sand	3.689	3.018	1.222	.237	
Coarse sand	-.489	.811	-.603	.554	
Medium sand	.583	.533	1.094	.287	
Fine sand	-.038	.445	-.085	.933	
Very fine sand	.872	.375	2.323	.031	
Silt	-1.408	.525	-2.683	.015	
Clay	.921	.656	1.404	.176	

Table 2. The clay minerals vermiculite and smectite showed significant positive correlations with SOCs (r=0.44 and r=0.41), also with labradorite which correlated with SOCs (r=0.48). These correlations indicated that increased vermiculite, smectite and labradorite have increased the SOCs. Soil fraction and SOC are not significantly correlated.

On the other hand, simultaneously, clay minerals (labradorite, smectite, chlorite and vermiculite) and soil fraction gave a significant difference to SOCs, 70.5% (R^2=0.705) (Table 2). In previous research by Zeraatpishe dan Khormali (2012), they found that SOCs are dependent on illite and chlorite occupancy. The presence of smectite and vermiculite to influence SOCs content corroborates the finding of (Singh *et al.* 2018; Singh *et al.* (2017). They reported that only smectite and vermiculite could regulate the SOCs. Nonetheless, this study showed that not only smectite, vermiculite and chlorite could affect the SOCs, but also labradorite. The presence of labradorite affecting SOCs has not been much discussed. Therefore, this phenomenon could happen considering labradorite is a mineral with a surface charge (Casey *et al*., 1989; Wypych and de Freitas, 2022). Labradorite, which belongs to the tectosilicate group, exhibits a low surface charge, but it is possibly involved in a range of chemical processes and demonstrates adsorption phenomena (Tan, 2010). Consequently, it is plausible that labradorite plays a role in modulating SOC. Electrostatic attraction and polyvalent cation bridging can occur during SOC adsorption processes by clay minerals (Singh *et al*., 2016).

The regression analysis also revealed that the soil percentage had a significant influence on SOC levels, which differed from the correlation analysis, which revealed no significant correlation (Table 1). Only the very fine sand fraction and the silt fraction have the potential to influence SOCs levels, resulting in the very fine sand fraction contributing favorably (positive slope value) and the silt fraction contributing adversely (negative slope value). The very fine sand fraction has a higher capacity to retain organic carbon than the medium and coarse fractions, which explains its ability to considerably affect SOCs (Lupi *et al*., 2021). This observation corresponds with the result of a study by Jindaluang *et al.* (2013), who identified that SOC improved rapidly in finer soil fractions than coarse fractions. According to Li *et al.* (2022), fine-textured soils have a greater potential to stabilize SOCs and this is triggered by higher soil moisture in finer-textured soils. The conclusions of this investigation, which revealed that the very fine sand fraction had a substantial positive association with SOCs, were also mostly in line with the research results of (Merabtene *et al*., 2021). They observed that only the coarse dust fraction had a favorable influence on SOCs.

CONCLUSION

Soils at 900 m d.f.s demonstrated the lowest bulk density. Soil fraction size was dominated by fine sand, particularly in SD and DT, where their amount was increased with increasing distance from the shoreline. Organic-C and CEC levels were extremely low, with the highest values reported at 900 m d.f.s. The average level of total SOCs is 34.18-59.20 MgC ha^{-1}, with the highest level found at 900 m d.f.s. in SD. The clay minerals and soil fraction size affecting the SOCs of coastal areas are labradorite, smectite, vermiculite, chlorite and very fine sand.

ACKNOWLEDGEMENT

We thank the Institution of Research and Community Services (LPPM) at Universitas Malikussaleh for funding this research through PNBP Grant Year 2022.

Conflict of interest: None.

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