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MODELLING SOIL ORGANIC CARBON IN MAJOR AGRICULTURAL AREAS OF JAVA ISLAND INDONESIA

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ABSTRACT

Agricultural practices that rely solely on inorganic inputs without amelioration with organic matter to the soil will rapidly decrease the soil organic carbon (SOC) content. This study sought to determine the status of SOC levels, to determine the correlations between SOC and several soil chemical properties, and to determine the equation model to estimate SOC levels in agricultural soils of Java Island. The soil sampling was conducted in 2012 followed by various laboratory analysis to reveal the soil chemical properties of agricultural soil in Java Island, Indonesia. The correlation analysis among soil chemical properties was conducted to see the relationship between SOC and the soil chemical properties. Models to relate the SOC content and the soil chemical properties were obtained using regression analyses. The results showed that the SOC content in Java varied from low, medium to high status. The SOC content had positive correlation ($p<0.01$) with total nitrogen (N); and oxides of aluminum (Al), iron (Fe) and silicon (Si) extracted by ammonium oxalate (Al_o, Fe_o and Si_o). SOC also had positive correlation ($p<0.01$) with elevation, Al extracted by dithionite citrate bicarbonate (Al_d), and $Al_o + \frac{1}{2} Fe_o$ (andic property). SOC did not have correlation with oxides of Fe and Si extracted by dithionite citrate bicarbonate (Fe_d and Si_d). The best equation model to estimate SOC by excluding total N was SOC = $1.43 + 0.035\ Al_o + 0.016\ Fe_o + 0.109\ Al_d - 0.007\ Fe_d - 0.124\ Si_o - 0.063\ Si_d - 0.0001$ elevation (R^2=0.872). The model indicated that Al_o, Fe_o, and Al_d were very important to predict SOC accumulation in Java Island, Indonesia.

Key words: crystalline oxide, elevation, regression

INTRODUCTION

Soil that meets the requirements for optimal plant growth must certainly have sufficient nutrient content. One important component that can determine the level of soil fertility is soil organic carbon (SOC) content. SOC content in the soil reflects the soil organic matter (SOM) content which is an important benchmark for better future soil management. SOC is part of the soil organic fraction that has degraded and decomposed either partially or completely and has undergone chemical and biological resynthesis.

Soil organic matter (SOM) has many benefits including improving soil structure, increasing available nutrients from the mineralization process of easily decomposed parts of organic matter, and increasing the diversity of organisms that can live in the soil. Indonesia is one of the countries in the humid tropics that is challenged by marginal problematic mineral soils due to the high rate of organic matter decomposition and nutrient leaching. SOC is generally low (< 2.00%) and soil pH is acidic (Brown et al. 2024).

Soil organic carbon (SOC) fractions are very important for understanding soil organic matter decomposition and stabilization. These fractions, with varying turnover rates, help model carbon cycling and assess soil health. The main types are particulate organic carbon (POC), mineral-associated organic carbon (MAOC), and pyrogenic carbon (Pyc). POC is the most labile with a high turnover rate and is sensitive to land use changes like tillage and crop rotation that can affect its contribution significantly (Leifeld and Kögel-Knabner 2004; Liu et al. 2024). MAOC is more stable than POC and is associated with soil minerals phyllosilicate, iron (Fe) and aluminum (Al) hydrous oxides (Dobarco et al. 2023; Zhang et al. 2024).

Even though SOC fractions are important but in a developing country like Indonesia, soil fertility is assessed using the data of SOC content, which is obtained by NC autoanalyzer or Walkley and Black method (Walkley and Black 1934). SOC levels of agricultural soils in Java Island, in general, are reported very low to low due to intensive cultivation with the addition of high rates of inorganic fertilizers, while very little organic matter is returned back to the soils. Efforts that must be made to restore these degraded agricultural soils can be achieved by adding organic matter to the soils so that there will be a gradual increase in soil organic matter content. The resulting accumulation of soil organic matter, together with SOC conservation efforts, can improve the quality of degraded soils, which in turn can contribute to increasing the productivity of cultivated commodities.

Soil organic carbon (SOC) content is generally related to oxides of Al and iron Fe, which are extracted using ammonium oxalate at pH of 3.00 (Ashida et al. 2021; Lyu et al. 2024). It is possible to have other soil properties to relate to SOC content, such as hydrous oxides of Al, Fe, and silicon (Si) extracted by dithionite-citrate-bicarbonate.

Based on the above explanations, a better understanding of the relation between SOC accumulation with soil chemical properties, in particular the oxides of Al, Fe, and Si is needed. This is important in order to restore degraded tropical mineral soils due to lowering SOC content through organic matter amelioration. This study sought to determine the status of SOC content levels, to determine the correlation between SOC content and several soil chemical properties, and to determine the equation model to estimate SOC levels in agricultural soils of Java Island, Indonesia.

MATERIALS AND METHODS

The soil samples were collected in 2012 in a design to obtain varying SOC data from agricultural soils in Java. The location of soil samples collected is presented in Figure 1. The soil samples were collected from agricultural soil both upland soils and paddy field soils. Each soil sample was collected from 0-30 cm depth compositely from 10 points representing the intended area (Tan 2005).

Although the soil chemical properties were mostly analyzed in 2013, it is still relevant to be used for building mathematical equation models because the data were from the soil samples collected in the same year so the equation obtained is valid and could be used to estimate soil organic carbon for different locations. The number of soil samples collected were 48 samples from 48 locations. The number of location was assumed to represent the various agricultural soils in West Java, Central Java and East Java.

Soil samples were air-dried for one week. After that, soil samples were crushed and sieved using 2mm-sieve to have proper size for soil analyses. Before soil analyses, the water content of the air-dried weight was determined to calculate the oven-dried weight (105 ºC) of the soil samples collected.

P = Paddy field, U = Upland

Figure 1. Location of soil sample collection
Source: (Yanai et al. 2014, with modification)

The data were used in this research were elevation, SOC content, total N, extracted Al, Fe, and Si using dithionite-citrate-bicarbonate (DCB method), and extracted Al, Fe, and Si using ammonium oxalate pH 3.00 (oxalate method). The DCB method extracts free and crystalline Al, Fe, and Si oxides, while oxalate method extracts the non-crystalline and poorly crystalline (hydrous oxide) forms of Al, Fe, and Si in soils. The data of SOC content, total N, extracted Al, and Fe, using dithionite-citrate-bicarbonate (DCB method), and extracted Al, Fe, and Si using ammonium oxalate pH 3.00 (oxalate method) referred to Yanai et al. (2014) and Hartono et al. (2015).

Elevation was determined using GPS, SOC and total N were determined using a NC autoanalyzer. Dithionite-citrate-bicarbonate Al and Fe hydrous oxides were extracted using dithionite-citrate-bicarbonate by the method of Mehra and Jackson (1960) hereafter referred to as Al_d, Fe_d, and Si_d. Oxalate-extractable Al, Fe and Si oxides were extracted using ammonium oxalate pH 3.00 for 4 hours in a dark room by the method of McKeague and Day (1966) hereafter referred to as Al_o, Fe_o, and Si_o. The extracted Al, Fe and Si by these two methods were determined using Inductively Coupled Plasma (ICP). All analyses were conducted at the Soil Science Laboratory, Kyoto University, Japan.

Analysis of variance (ANOVA) was used to determine the effect of location on SOC content in paddy fields and upland soils. The locations were West Java, Central Java and East Java. The mean difference test was conducted using the Tukey test at an alpha level < 0.05. Systat 13 (SPSS Inc. 1998) was used for the analysis.

A simple correlation analysis was conducted to see the relationship between SOC content and the selected soil chemical properties. The Pearson correlation test was used to have the significance of the correlation. Models to relate the SOC content and the selected soil chemical properties were obtained using regression analyses. Systat 13 (SPSS Inc. 1998) was used for the analysis.

RESULTS AND DISCUSSION

Selected soil chemical properties and status of soil organic carbon (SOC) content in Java Island
The site name, longitude, latitude, soil order and elevation of paddy fields were presented in Table 1, as well as the Al_o, Fe_o, Al_o+1/2Fe_o, Si_o, Al_d, Fe_d, Si_d, total C and total N content of paddy fields. Overall, the SOC content of paddy field in Java Island ranged from very low to low SOC, but some locations had medium status distributed in West Java, Central Java, and East Java (Soepraptohardjo et al. 1983). This low SOC content in paddy field of Java Island was reported by Hartono et al. (2015). Low SOC levels in paddy fields could be caused by the removal of harvested straw from the field and also due to rotation from paddy field to other crops in the dry season (Chen et al. 2016).

The site name, longitude, latitude, soil order and elevation of upland soil samples were presented in Table 2. The SOC content in upland soil of West Java ranged from 9.65 to 79.4 g kg^{-1}. In Central Java the SOC content of upland soil ranged from 7.55 to 21.6 g kg^{-1} while in East Java the SOC content of upland soil ranged from 9.12 to 49.8 g kg^{-1}.

For upland agricultural soil, carbon loss occurs through increased decomposition of organic matter in the tillage layer due to tillage and erosion. The decrease in SOC levels in upland soil through tillage can occur through mechanisms such as mixing between organic matter-rich upper horizons and relatively organic matter-poor lower layers, accelerated mineralization due to increased tillage intensity, erosion, and low C inputs (Jakab et al. 2023). The range of soil organic content is highly variable and influenced by a combination of soil type, management practices, and environmental conditions (Lim et al. 2022; Matus et al. 2024). Andosols order exhibited much higher SOC content especially the Andosols which occupy the high upland which is about 1600 m above sea level as shown in West Java in Sagalaherang and Lembang and as shown in East Java in Brawijaya University farm, Batu (Table 2).

Soil samples that do not belong to Andosols order exhibited a SOC content of very low to low status (Soepraptohardjo et al. 1983). Andosols order showed very high status of SOC content. Andosols had high amounts of ammonium oxalate pH 3.00-extractable Al, Fe and Si oxides known also as short-range order clay minerals. Short-range order clay minerals have a high capacity to bind SOC. The strong bonding between short-range order clay minerals with SOC protects the SOC from decomposition by soil organisms. This aligns with Lenhardt et al. (2022), stating that carboxyl groups in organic matter strongly bind to structural Al on the surface of allophane spheres (inner sphere complexation). Stabilization of organic matter in soil through interaction with structural Al is important for maintaining soil quality and slowing decomposition of soil organic matter. Some degradation products of non-humified materials are bound by clay containing short-range order clay minerals, making this organic matter difficult for microorganisms to decompose. Higher Al_o + ½Fe_o levels in Andosols indicate high levels of allophane and imogolite in the soil. Soils containing allophane and imogolite will interact with soil organic matter to form stable allophane-organic or imogolite-organic complexes, protecting the organic fraction from degradation (Matus et al. 2014).

Andosols develop from volcanic ash and are characterized by high soil organic matter content, good physical properties, and comparable anion and cation exchange capacities (Manuel et al. 2022). The mineral clay of Andosol consists of allophane, imogolite, and short-range order Fe and Al hydrous oxides (Candra et al. 2021). Allophane is a group of clay minerals composed of Si, Al, and water in chemical combination (Margenot et al. 2017). High stability of soil organic matter in Andosols is related to the presence of "active Al," a term referring to Al residing in Al-humus complexes and allophanic clay (Takahashi and Dahlgren 2016). High Al_o levels lead to stable soil aggregates offering physical protection to SOC. Short-range order clay materials are crucial for stabilizing and aggregating SOC in allophanic Andosols (Asano and Wagai 2014).

Table 1. Location of collected samples in paddy fields and their selected soil properties

Site Name	Longitude S	Latitude E	Soil order according to FAO	Elevation (m)	Al_o (g kg^{-1})	Fe_o (g kg^{-1})	Al_o+1/2Fe_o (g kg^{-1})	Si_o (g kg^{-1})	Al_d (g kg^{-1})	Fe_d (g kg^{-1})	Si_d (g kg^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})
West Java													
Palimanan	06°40' 52.3"	108°25' 32.6"	Fluvisols	28	1.11	4.61	3.42	0.75	0.70	6.25	2.31	8.06	0.78
Indramayu	06°24' 57.7"	108°16' 33.2"	Fluvisols	23	1.81	7.09	5.35	0.61	1.37	10.5	1.36	17.2	1.97
Jatisari	06°21' 26.4"	107°32' 36.9"	Fluvisols	45	1.49	12.7	7.86	0.25	1.01	15.7	1.40	21.6	2.19
Karawang	06°16' 25.0"	107°17' 08.7"	Fluvisols	31	1.47	14.8	8.86	0.42	1.06	15.5	1.59	23.2	2.29
Cikarawang	06°33' 05.1"	106°44' 22.4"	Acrisols	195	8.86	27.5	22.6	1.02	4.83	54.1	1.49	23.6	2.35
Pamanukan	06°16' 43.4"	107°50' 39.2"	Fluvisols	22	1.63	9.3	6.29	0.41	1.27	12.1	1.89	27.0	2.52
Cicalengka	07°06' 07.3"	108°06' 09.6"	Andosols	785	6.60	28.5	20.9	0.66	5.11	40.7	1.75	28.9	2.90
Central Java													
Jogjakarta	07°49' 49.3"	110°27' 21.4"	Luvisols	103	3.94	14.0	10.9	0.47	1.54	5.56	1.59	8.97	1.00
Brebes	06°52' 32.5"	109°03' 46.6"	Fluvisols	19	1.74	8.03	5.76	0.89	1.03	9.65	1.81	13.1	1.37
Jekulo	06°48' 07.8"	110°56' 02.7"	Nitosols	29	1.74	10.2	6.8	1.02	1.90	12.7	1.91	14.6	1.42
Borobudur	07°34' 39.0"	110°15' 01.8"	Luvisols	318	6.17	11.5	11.9	0.82	1.90	5.49	1.88	14.7	1.51
Demak	06°55' 46.7"	110°32' 38.7"	Fluvisols	16	1.75	6.39	4.94	0.83	1.26	9.33	1.29	15.9	1.59
Suradadi	06°52' 24.2"	109°15' 02.0"	Nitosols	23	1.73	8.12	5.79	0.79	1.22	11.5	1.35	16.0	1.73
Kutoarjo	07°43' 26.4"	109°52' 20.5"	Acrisols	23	7.31	26.4	20.5	0.95	2.78	19.9	2.91	18.6	1.83
Karanganyar	07°37' 36.1"	109°33' 55.4"	Acrisols	22	7.00	32.1	23.0	0.67	2.71	22.1	3.00	19.8	1.91
Kendal	06°56' 29.5"	110°14' 36.1"	Luvisols	19	1.74	11.5	7.50	0.76	1.10	14.6	1.87	24.0	2.32
Buntu	07°35' 24.2"	109°15' 07.3"	Fluvisols	18	9.90	40.8	30.3	1.28	3.64	22.4	2.31	27.0	2.65
Batang	06°58' 39.3"	109°53' 39.1"	Nitosols	178	2.22	10.4	7.42	0.76	2.47	20.0	2.11	29.9	2.95
East Java													
Jombang	07°31' 48.1"	112°15' 24.8"	Luvisols	39	3.32	2.87	4.76	0.56	1.05	2.45	1.87	9.78	0.97
Tambak Rejo	07°15' 54.7"	111°35' 10.9"	Vertisols	79	1.39	1.86	2.32	0.76	0.86	3.00	1.02	10.8	0.86
Nganjuk	07°33' 56.7"	111°50' 34.3"	Fluvisols	74	5.37	1.21	5.97	0.89	1.01	3.65	2.06	14.9	1.36
Bojonegoro	07°08' 14.3"	111°48' 47.9"	Fluvisols	40	2.32	6.75	5.69	0.63	1.83	8.55	1.05	18.2	1.59
Ponorogo	07°51' 53.2"	111°27' 17.3"	Fluvisols	112	6.36	8.26	10.49	1.16	1.98	5.34	2.00	23.8	2.16

o = extracted using ammonium oxalate pH 3.00
d = extracted using dithionite-citrate-bicarbonate
Source: (Yanai et al. 2014; Hartono et al. 2015)

Table 2. Location of collected samples in upland and their selected soil properties

Site Name	Longitude S	Latitude E	Soi order according to FAO	Elevation (m)	Al_o ($g\ kg^{-1}$)	Fe_o ($g\ kg^{-1}$)	Al_o+1/2Fe_o ($g\ kg^{-1}$)	Si_o ($g\ kg^{-1}$)	Al_d ($g\ kg^{-1}$)	Fe_d ($g\ kg^{-1}$)	Si_d ($g\ kg^{-1}$)	Total C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)
West java													
Ciamis	07°18' 44.2"	108°17' 01.9"	Luvisols	326	6.84	14.5	14.1	1.48	3.77	27.6	1.02	9.65	1.03
Malangbong	07°07' 00.3"	108°07' 18.9"	Andosols	662	7.15	16.1	15.2	1.10	7.67	66.9	1.17	19.3	1.92
Bantar Kambing	06°30' 52.6"	106°41' 50.0"	Acrisols	140	11.4	34.2	28.5	0.81	7.00	66.4	0.96	20.9	2.10
Darangdan	06°40' 22.4"	107°25' 31.7"	Andosols	502	14.2	14.7	21.5	0.92	12.8	81.6	0.94	21.7	2.23
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	9.07	11.4	14.8	0.39	10.3	67.9	1.13	23.7	2.47
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	9.02	11.6	14.8	0.45	9.83	67.4	1.12	24.0	2.91
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	9.52	12.5	15.8	0.51	9.69	67.3	0.97	25.0	2.66
Cikabayan, Darmaga	06°33' 08.7"	106°42' 58.4"	Acrisols	190	10.7	11.3	16.3	0.48	9.50	67.3	0.96	25.6	2.58
Sagalaherang	06°40' 34.2"	107°40' 39.2"	Andosols	577	88.1	41.5	109	12.5	23.3	47.5	2.96	56.0	4.82
Lembang	06°48' 11.5"	107°38' 53.5"	Andosols	1239	176	59.2	205	30.9	22.8	32.8	2.38	70.2	6.79
Lembang	06°48' 20.0"	107°39' 22.4"	Andosols	1214	212	92.5	258	36.2	25.6	41.2	1.99	79.4	4.90
Central Java													
Borobudur	07°34' 48.5"	110°14' 52.2"	Luvisols	301	6.70	15.2	14.3	0.86	1.84	6.36	1.35	7.55	0.76
Wonogiri	07°49' 48.3"	111°05' 14.8"	Luvisols	351	5.67	19.3	15.3	1.63	4.10	41.9	2.64	12.5	1.21
Kudus	06°43' 17.5"	110°52' 36.7"	Nitosols	213	3.61	7.23	7.23	0.83	3.83	15.4	1.43	13.4	1.27
Wonosari	07°55' 32.9"	110°33' 50.2"	Vertisols	217	5.45	31.3	21.1	2.35	3.28	40.3	3.46	13.8	1.23
Batang	06°56' 51.2"	109°47' 11.7"	Nitosols	91.0	1.86	7.78	5.75	0.80	2.56	18.9	1.94	17.3	1.80
Lumbir	07°28' 25.9"	108°58' 58.5"	Acrisols	67.0	9.62	17.2	18.2	0.83	5.19	35.3	1.43	21.6	2.15
East Java													
Bancar	06°46' 24.6"	111°44' 08.1"	Luvisols	19.0	0.82	1.11	1.38	0.47	1.01	4.43	2.89	9.12	0.82
Batu, Malang	07°52'58.84"	112°32'23.5"	Andosols	835	8.64	23.4	20.4	1.30	3.10	13.6	3.28	11.5	1.21
Tambak Rejo	07°15' 54.7"	111°35' 10.9"	Vertisols	79.0	1.76	1.40	2.46	0.91	0.94	2.74	0.96	11.8	0.95
Tuban	06°54' 24.4"	112°12' 14.0"	Luvisols	40.0	2.23	3.88	4.17	0.85	4.61	59.7	1.93	13.2	1.50
Tulungagung	08°06' 27.2"	112°02' 17.4"	Fluvisols	131	10.5	10.5	15.7	6.47	3.08	4.17	1.92	13.6	1.18
Paciran	06°52' 39.7"	112°24' 47.7"	Luvisols	28.0	2.51	5.26	5.14	1.29	4.38	55.3	1.92	14.9	1.85
Ngantang	07°53' 18.8"	112°21' 41.0"	Andosols	693	15.2	20.9	25.7	3.07	3.31	9.77	1.90	15.5	1.65
Brawijaya University Farm, Batu	07°44' 24.7"	112°32' 15.0"	Andosols	1664	67.7	34.7	85.0	10.4	14.2	15.3	2.17	49.8	4.70

o = extracted using ammonium oxalate pH 3.00
d = extracted using dithionite-citrate-bicarbonate
Source: (Yanai et al. 2014; Hartono et al. 2015)

The SOC levels of paddy fields in Java Island were not statistically different (Table 3). As for upland soils, the SOC levels of upland soils in Java Island were not different either (Table 4). West Java and East Java upland soils had higher SOC content than Central Java (Table 4). Some samples from West Java and East Java were Andosols.

Table 3. The effect of location to the SOC content in paddy field soil.

Province	**Number of sample**	**SOC (g kg^{-1})**
West Java	7	18.7a
Central Java	11	18.4a
East Java	5	15.5a

Means followed by the same letter within a column are not significantly different (Tukey's test, *p*<0.05)

Table 4. The effect of location to the SOC content in upland soil

Province	**Number of samples**	**SOC (g kg^{-1})**
West Java	11	34.1a
Central Java	6	14.4a
East Java	8	17.4a

Means followed by the same letter within a column are not significantly different (Tukey's test, *p*<0.05)

Correlation between SOC and selected soil properties. The correlation was established using all soil properties data from paddy field soils and upland soils. Based on Pearson correlation, SOC content of agricultural soils in Java Island had a very significant correlation ($p < 0.01$**) with total N, Al_o, $Al_o + ½Fe_o$, Al_d, Fe_o, Si_o, and elevation (Table 5). This indicates a strong relationship between SOC content and total N. Higher SOC content correlates with higher total N content. Furthermore, higher Alo + ½Feo, Alo, Ald, Feo, Sio, and elevation also correlate with higher SOC content.

Table 5. Correlation among selected soil properties

	Total N	**$Al_o + ½Fe_o$**	**Al_o**	**Al_d**	**Si_o**	**Fe_o**	**Elevation**	**Fe_d**	**Si_d**
SOC	0.956**	0.911**	0.906**	0.874**	0.868**	0.818**	0.679**	0.276	0.146
Total N		0.806**	0.803**	0.845**	0.756**	0.719**	0.656**	0.349*	0.111
$Al_o + ½Fe_o$			0.996**	0.861**	0.982**	0.893**	0.721**	0.181	0.221
Al_o				0.860**	0.989**	0.847**	0.713**	0.159	0.194

	Total N	**Al_o + ½Fe_o**	**Al_o**	**Al_d**	**Si_o**	**Fe_o**	**Elevation**	**Fe_d**	**Si_d**
Al_d					0.805**	0.754**	0.709**	0.550**	0.059
Si_o						0.821**	0.687**	0.091	0.217
Fe_o							0.667**	0.267	0.324*
Elevation								0.188	0.187
Fe-d									-0.233

** Very significant ($p<0.01$)
* Significant ($p<0.05$)

SOC content had significant correlations with total N, Al_o, Al_o + ½Fe_o, Al_d, Fe_o, Si_o, and elevation (Table 4), suggesting that a model to relate SOC in Java agricultural areas is feasible. SOC content also significantly correlated with elevation. High elevation areas have low temperature that slows organic matter decomposition. High elevation causes low air and soil temperatures (Serrano et al. 2020). Climatic factors like temperature affect SOC content (Jiang et al. 2023), where higher elevation leads to lower temperatures, increasing total SOC content (Tan et al. 2020).

Organic matter provides nutrients such as N, P, and S through microbial mineralization processes. Higher organic matter levels result in higher total N content. Positive correlations of SOC content with total N and Al_o + ½Fe_o levels indicate the influence of volcanic materials on organic matter accumulation in Java's agricultural soils (Yanai et al. 2014) . Volcanic eruptions produce pyroclastic materials, forming Andosol soil order. Weathering of volcanic ash produces allophane and imogolite, increasing alongside rising levels of Al_o + ½Fe_o (ammonium oxalate extraction). Al and Si contents, extracted with ammonium oxalate (Al_o, Si_o), estimate the presence of allophane and imogolite. Positive correlations between Al_o + ½Fe_o and Al_o, Fe_o, and Si_o reflect the relationship between short-range order clay minerals and Al, Fe, and Si extracted by ammonium oxalate. Soil fractions of Fe, Al, and Si can be crystalline clay minerals, short-range order clay minerals, or humus complexes. Chemical separation for those forms of Al, Fe hydrous oxides and Si amorphous and crystalline uses dithionite-citrate, ammonium oxalate, and sodium pyrophosphate solutions (Boland et al. 2012).

Model to predict soil organic carbon (SOC) accumulation. Significant correlations between SOC content and selected soil properties (Al_o, Al_o + ½Fe_o, Al_d, Fe_o, Si_o, and elevation) enable the formulation of empirical models to relate SOC content with these selected soil properties. In this model, total N was excluded in the models because SOC and total N are very correlated each other. This model, in turn, can be used to predict the causes of SOC accumulation. Model to predict SOC content using soil data from paddy field and upland field existing in the soil as a result of soil development including the effect of soil management such as returning rice straw to the field.

Multiple linear regression equations derived from this soil samples data were shown in Table 6. High R^2 values indicated model suitability. Smith (2015) emphasized selecting regression equations based on statistical criteria, particularly the coefficient of determination R^2 and practical considerations.

Table 6. Model to predict SOC in paddy field and upland soils

Model	Equation	R^2
1	$SOC = 1.43 + 0.035\ Al_o + 0.016\ Fe_o + 0.109\ Al_d - 0.007\ Fe_d - 0.124\ Si_o - 0.063\ Si_d - 0.0001$ elevation	0.872
2	$SOC = 1.43 + 0.036\ Al_o + 0.015\ Fe_o - 0.127\ Si_o + 0.099\ Al_d - 0.006\ Fe_d - 0.062\ Si_d$	0.871
3	$SOC = 1.33 + 0.039\ Al_o + 0.013\ Fe_o - 0.136\ Si_o + 0.095\ Al_d - 0.005\ Fe_d$	0.871
4	$SOC = 1.218 + 0.011\ Al_o + 0.016\ Fe_o + 0.130\ Al_d - 0.007\ Fe_d$	0.865
5	$SOC = 1.20 + 0.017\ Al_o + 0.013\ Fe_o + 0.086\ Al_d$	0.862
6	$SOC = 1.43 + 0.027\ Al_o + 0.015\ Fe_o$	0.829
7	$SOC = 1.61 + 0.032\ Al_o$	0.820
8	$SOC = 1.45 + 0.027\ Al_o + ½\ Fe_o$	0.829

The ideal model was $SOC = 1.43 + 0.035\ Al_o + 0.016\ Fe_o + 0.109\ Al_d - 0.007\ Fe_d - 0.124\ Si_o - 0.063\ Si_d - 0.0001$ elevation (R^2=0.872). Figure 2 compares predicted SOC by model 1and actual SOC values. Even though in correlation, Si_o had positive constant with SOC content, but in equation models, Si_o had a negative constant for predicting SOC accumulation.

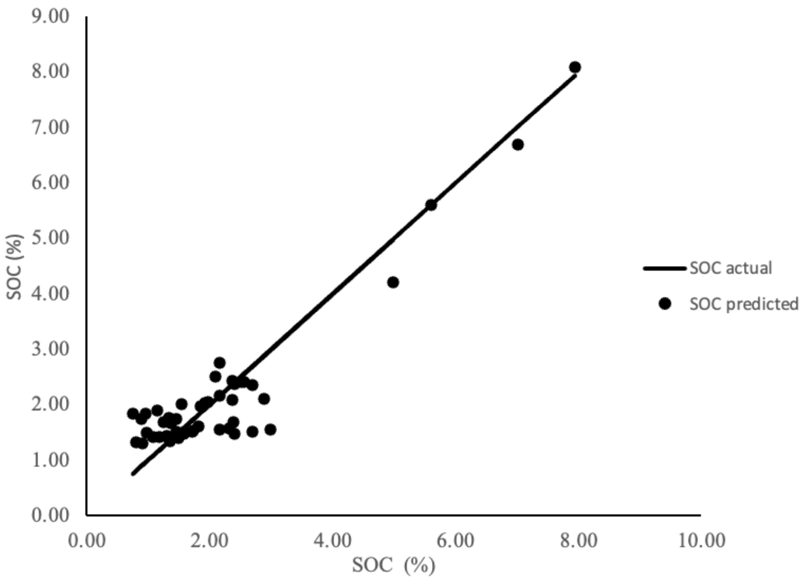

Figure 2. Plotting actual SOC and predicted by model 1

Another suitable model, SOC = 1.43 + 0.036 Al_o + 0.015 Fe_o - 0.127 Si_o + 0.099 Al_d - 0.006 Fe_d - 0.062 Si_d (R^2=0.871), lacks elevation data yet remains effective. Figure 3 compares the SOC accumulation predicted using model 2 with the actual SOC values. Although Si_o positively correlates with SOC content, its negative constant in prediction models indicates that Al_o, Al_o + ½Fe_o, Al_d, and Fe_o are better predictors.

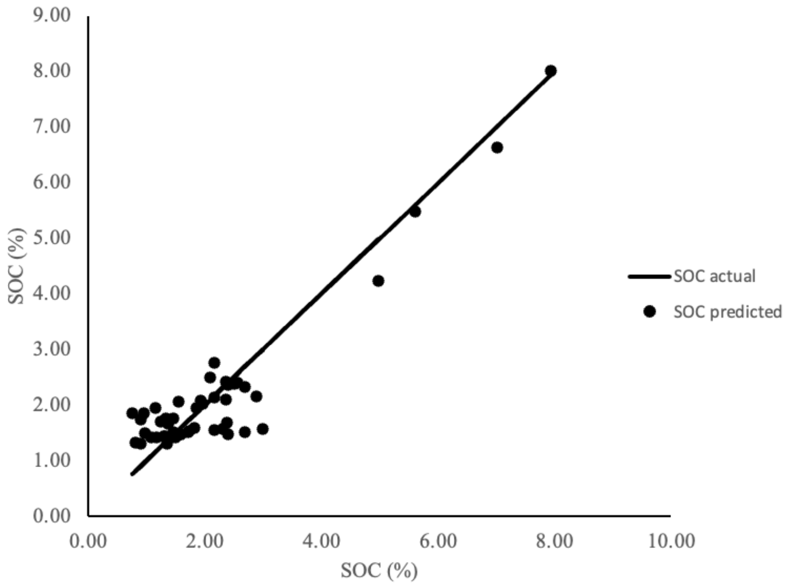

Figure 3. Plotting actual SOC and predicted by Model 2

Figure 4 compares the SOC accumulation predicted by model 8 with actual values. Al, Fe extracted by ammonium oxalate (Al_o, Fe_o, and Al_o + ½Fe_o) positively contribute to SOC prediction, indicating increased SOC stability due to binding by short-range order clay minerals.

The best model to predict SOC accumulation was SOC = 1.43 + 0.035 Al_o + 0.016 Fe_o + 0.109 Al_d - 0.007 Fe_d - 0.124 Si_o - 0.063 Si_d - 0.0001 elevation (R^2=0.872). Model 2 (SOC = 1.43 + 0.036 Al_o + 0.015 Fe_o - 0.127 Si_o + 0.099 Al_d - 0.006 Fe_d - 0.062 Si_d (R^2=0.871) was also effective, though inclusion of elevation data improves prediction accuracy.

Those models are very important in identifying the soil properties that control the SOC accumulation. The models show that Al_o and Fe_o or the non-crystalline and poorly crystalline (hydrous oxide) of Al and Fe, or amorphous Al and Fe, are the main components in controlling SOC accumulation. In addition, Al_d, the more crystalline of Al oxide, also controls SOC accumulation. The high amount of Al_o, Fe_o and Al_d increases the amount of SOC content in the soils. Ligand exchange between carboxyl and hydroxyl groups of organic compounds and mineral surfaces is a key adsorption mechanism (Gu et al. 1994). As a result, carboxylic acids like oxalic acid show high adsorption affinity to clay minerals, especially iron oxides (Jagadamma et al. 2012; Jagadamma et al. 2014; Yeasmin et al. 2014).

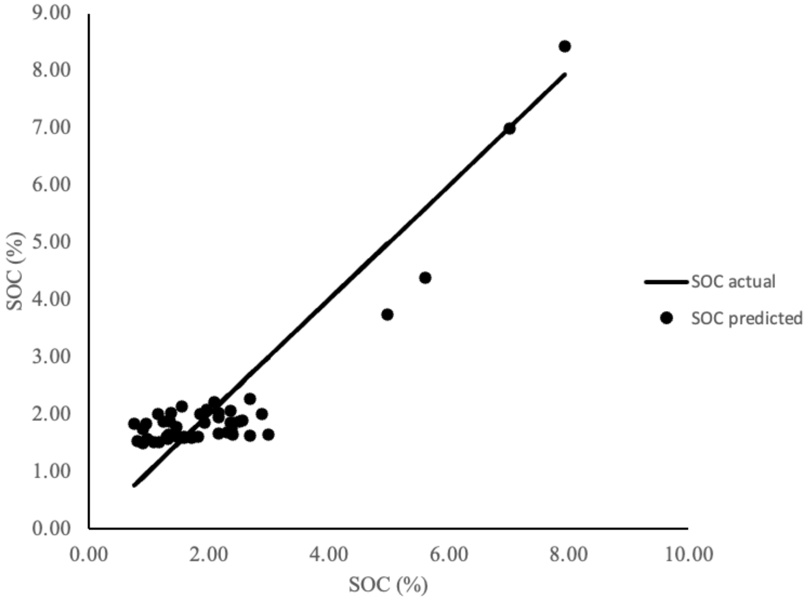

Figure 4. Plotting actual SOC and predicted by Model 8

The models obtained in this research are very location-specific. Different places have different models for predicting SOC accumulation. In China, in coastal wetlands, multiple linear regressions and random forest model showed that soil pH was the most important variable impacting SOC, followed by Cl and silt content (Zhang et al. 2017). In Calabar, Cross River State, Nigeria, the Ca to Mg ratio, effective CEC, base saturation, and K to Ca ratio had a significant influence on SOC distribution in that area (John et al. 2020). Therefore, the models obtained in this study indicate that Al_o, Fe_o, and Al_d are very important to predict SOC accumulation in soils of Java Island, Indonesia.

CONCLUSION

Soil organic carbon (SOC) in Java Island's agricultural soils ranges from low to high, influenced by short-range order clay minerals. SOC is significantly correlated with total nitrogen, Alo, Feo, Ald, Sio, and elevation. Higher values of these factors correspond to higher SOC levels. The most effective model to predict SOC accumulation, according to the coefficient of determination (R^2), was SOC = 1.43 + 0.035 Al_o + 0.016 Fe_o + 0.109 Al_d - 0.007 Fe_d - 0.124 Si_o - 0.063 Si_d - 0.0001 elevation (R^2=0.872). The equations could be valid and relevant to estimate SOC of different years due to high R^2 values, which are close to 1.00 although the soil data were collected in 2012.

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