



## Aggregate characteristics and aggregate-associated soil organic carbon and carbohydrates of soils under contrasting tree land use

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### ABSTRACT

Protection of soil organic carbon and acid-hydrolyzable carbohydrates in aggregate-size fractions is important for appraising soil degradation and aggregation under land use types. Aggregate-associated soil organic carbon (SOC) and acid-hydrolyzable carbohydrates (R-CHO) in bulk soils and aggregate-size fractions of a sandy loam soil under Alchornea bush, Rubber, Oil palm and Teak plantations in southern Nigeria were studied. Results revealed significant differences in aggregate-associated SOC and R-CHO, bulk densities, total porosity, soil organic carbon stock and aggregate stability among the land use types. Greater SOC was stored in macro-aggregates >0.25 mm, while greater R-CHO was occluded in micro-aggregates <0.25 mm ( $p < 0.05$ ). The highest mean weight diameter (MWD) was 1.01 mm in Alchornea soils and 0.92 mm in Oil palm plantation at 0-15 cm topsoil. Soil organic carbon stock in 0-15 cm topsoil was 77.7, 81.8, 92.2, and 67.5 kg C ha<sup>-1</sup> in Alchornea, Rubber, Oil palm, and Teak soils, respectively. Relationships showed a positive linear correlations between MWD and SOC ( $r = 0.793$ ,  $p < 0.05$ ) and R-CHO ( $r = 0.789$ ,  $p < 0.05$ ). Alchornea bush and Oil palm plantation increased macro-aggregate formation and macro-pores >5  $\mu$ m, therefore they have greater potentials to boost protection of SOC in soil macro-aggregates.

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### 1. INTRODUCTION

Soil organic carbon storage in relation to aggregate hierarchy is driven by land use, organic and inorganic input, and organic matter stabilizing processes (Carrizo et al., 2015; Gentile et al., 2011). The location of soil organic carbon (SOC) in the hierarchical structure of soil aggregates determines the storage and transformation of SOC. Soil organic C accumulation and turnover have been used to assess the formation and stability of soil aggregates (Cates et al., 2016; Gupta & Germida, 2015). Various authors have reported changes in aggregate-associated soil organic carbon and aggregation due to land-use systems (Cates et al., 2016; Udom & Ogunwole, 2015).

Carbohydrates (R-CHO) constitute a portion of the labile carbon pool in the soil, and as bonding agents for soil aggregates and energy sources for soil microorganisms (Maqubela et al., 2012). It represents a substantial portion of

soil organic matter fraction, which confers stability to soil aggregates (Yousefi et al., 2008; Zhang et al., 2012). Various extractable forms of carbohydrates, including hot water-extractable and dilute acid-extractable carbohydrates are involved in the stabilization of soil aggregates. Studies revealed that carbohydrates are sensitive to land-use and management (de Souza et al., 2016) and that the labile carbon pool is sensitive to changes in land-use systems. The roles of polymeric carbohydrates on the aggregate stability of some soils have also been reported (Ratnayake et al., 2013). However, literature showed considerable controversy on the actual role of carbohydrate fractions on the aggregate stability of soils.

In the tropics, differences in opinion exist on the actual fraction of SOM that is responsible for soil aggregation. For example, Zhao et al. (2017) reported that organic matter

fractions rather than the amount per se modified aggregate stability of the soil. While Annabi et al. (2011); Duchicela et al. (2013); Guo et al. (2019); Guo et al. (2018); Sun and Lu (2014) found a direct correlation between total SOM content and aggregate stability. In contrast, Carrizo et al. (2015) found no such positive correlations in similar studies, while Anaya and Huber-Sannwald (2015) reported different results for different types of organic matter fractions. Martins et al. (2012) found that the carbohydrate (R-CHO) pool was not effective in the stability of soil aggregates, while Lykhman et al. (2020) found that R-CHO was involved in aggregate stability in the presence of humified SOM pool.

Other studies observed that due to the temporary biological stability and rapid degradation of carbohydrates, their long-lasting role in soil aggregation differed in certain soil conditions, especially in the tropics (Albaladejo et al., 2013; Parwada & Van Tol, 2017; Yilmaz et al., 2019). Carrizo et al. (2015) found that differences in plant cover, soil characteristics, types of extractable carbohydrates (cold or hot water or acid-hydrolyzed), influenced micro-and macro-aggregate stability of soils. Whereas, Zubair et al. (2012) observed that carbohydrates extracted by hot water and dilute acid were suitable indicators for soil quality assessment, particularly in relation to soil aggregation. Debosz et al. (2002) found that hot-water extractable carbohydrates were higher in micro-aggregates than in macro-aggregates.

In relation to aggregate characteristics, Zhang et al. (2012) discussed soil aggregation and aggregating agents under long-term contrasting land use and found that smaller macro-aggregates (WSA 0.25-2 mm) had a larger accumulation of SOC and higher aggregate stability. Udom et al. (2016) reported that macro-aggregates (>0.25 mm) were effective in the protection of soil organic C against losses. Other studies (Zhang et al., 2016), observed that C derived from an invasive C4 grass Spartina was mainly distributed in macro-aggregates, while C from a native C plant Suaeda salsa was mostly found in micro-aggregates and free silt-sized fractions. Guan et al. (2015) found that additions of organic residues to the soil altered the distribution of SOC in aggregate-size fractions, especially in macro-aggregates (>250 µm). Udom and Simon (2020) obtained high SOC and carbohydrate concentrations in dry-sieved macro-aggregates of forested than cultivated soils. Other studies such as Zhang et al. (2016) found that organic C in micro-aggregates was less susceptible to change than in the macro-aggregates. Liu et al. (2014) and Nweke and Nwabude (2015) found that macro-aggregate stability was mainly due to the key roles of carbohydrate-associated-roots in well-structured soils. In other studies, the encrustation of SOM within micro-aggregates was discussed as the fundamental pathway to SOC stock and protection from rapid degradation (Udom & Ogunwole, 2015).

Literature suggests existing gaps in knowledge regarding the roles of organic carbon fractions and acid-hydrolyzable carbohydrates on soil aggregate structure under tree fallow farming systems. This will provide additional knowledge on the potential protection of soil organic C and acid-hydrolyzable carbohydrates in soil aggregates when these soils are converted to arable crop production. In this study,

we quantified aggregate-size distribution and aggregate-associated SOC and carbohydrates of soils under Alchornea (*Alchornea cordifolia*), Rubber (*Hevea brazillensis*), Oil palm (*Elaeis guineensis*) and Teak (*Tectonia grandis*). The objectives of this study were to (i) quantify soil organic carbon and carbohydrate distributions within macro-and micro-aggregate size classes under these plant species; and (ii) evaluate soil organic carbon stock and the potentials of these tree plant cultures in protecting soil aggregates from disruption.

## 2. MATERIALS AND METHODS

### 2.1. The study area and soil sampling

The study was carried out on a 250 ha land in Port Harcourt (4°15' N and 7°30' E), in Rivers State, Nigeria. The soil is classified as Arenic Acrisol (USDA, 2012). Mean annual rainfall in the area is more than 2000 mm in September and October. The mean annual maximum temperature is 30°C. Four land use areas were identified viz: (1) 20-year Alchornea bush (*Alchornea cordifolia*), (2) 20-year rubber plantation (*Hevea brazillensis*), (3) 15-year oil palm plantation (*Elaeis guineensis*), and (4) 20-year forested teak plantation (*Tectonia grandis*). Soil organic carbon, acid-extractable carbohydrates and lignin content of the plant residues from the different plant covers are presented in Table 1. Each land area was subdivided into 5 blocks (based on the physiographic position), giving a total of 20 plots of 50 x 50 m, for soil sample collections. Four replicates of disturbed and undisturbed soil samples were collected at 0–15 and 15–30 cm depths in each block. A total of 160 bulk and core soil samples were collected for laboratory analysis.

### 2.2. Determination of particle size-distribution, bulk density, and total porosity

Particle-size distribution was determined by the method of Gee and Or (2002). Bulk density was measured according to Grossman and Reinsch (2002) as:

$$\text{Bulk density} = \frac{M_d}{V_b} \quad [1]$$

where  $M_d$  is mass of oven-dried soil (g) and  $V_b$  volume of bulk soil  $\text{cm}^3$

Total porosity was determined by the method of Flint and Flint (2002) as:

$$\% \text{ Total porosity} = \frac{V_w}{V_b} \times 100 \quad [2]$$

Where  $V_w$  is volume of water ( $\text{cm}^3$ ), and  $V_b$  volume of bulk soil ( $\text{cm}^3$ )

Macro-porosity (pore size >5µm) was calculated as:

$$\% \text{ Macro-porosity} = \frac{\text{Volume of water drained at 10kPa}}{\text{Volume of bulk soil}} \times 100 \quad [3]$$

$$\% \text{ Micro-porosity} = \% \text{ Total porosity} - \% \text{ Macro-porosity} \quad [4]$$

The field capacity moisture content was measured at -10 kPa.

**Table 1.** Organic carbon, acid-extractable carbohydrate and lignin concentration in plant residues

Plant residues	Organic carbon (g kg <sup>-1</sup> )	Acid-extracted carbohydrate (g kg <sup>-1</sup> )	Lignin (g kg <sup>-1</sup> )
<i>Alchornea cordifolia</i>	559.2	367.3	107.5
Rubber	167.9	93.7	116.2
Oil palm	339.3	230.5	214.8
Teak	126.1	53.9	114.6

### 2.3. Saturated hydraulic conductivity and water holding capacity

Saturated hydraulic conductivity (Ksat) was measured by the constant head soil core method (Reynolds et al., 2002) and calculated as:

$$K_{sat} = \frac{Q}{(A \cdot T)} \times \frac{L}{\Delta H} \quad [5]$$

where Ksat is the saturated hydraulic conductivity (cm h<sup>-1</sup>), Q the volume of water (cm<sup>3</sup>) that drained through a cross-sectional area A (cm<sup>2</sup>), T is time (S), L is length of core (cm), and ΔH the hydraulic head difference (cm). Water holding capacity (WHC) at saturation was calculated as:

$$WHC = \frac{(M_w - M_d)}{M_d} \quad [6]$$

where Mw is the mass of wet soil (g) and Md the mass of oven-dried soil (g).

To obtain the macro-porosity the core samples were subjected to soil-water pressures of -10 kPa using the hanging water column method (Cassel & Nielsen, 1986).

### 2.4. Determination of organic carbon and organic carbon stock

Total organic carbon was determined by the wet oxidation dichromate method with H<sub>2</sub>SO<sub>4</sub> – K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>, followed by residual titration with 1 N HCl (Nelson & Sommers, 1996). Soil organic carbon for specific soil depth expressed as soil organic carbon stock (SOCS) was calculated and corrected to equivalent soil mass as described by (Marques et al., 2016) as:

$$SOCS_d = \sum (C \times \rho_b \times D \times 0.1) \quad [7]$$

where SOCS<sub>d</sub> is the SOC stock to specific soil depth d (kg C ha<sup>-1</sup>), C is the organic C content (g C kg<sup>-1</sup>), ρ<sub>b</sub> the soil bulk density (g cm<sup>-3</sup>), D the soil depth (cm), and 0.1 is the correction factor.

### 2.5. Aggregate fractionation and determination of carbohydrates and organic carbon

The physical fractionation procedure of Cambardella and Elliott (1992) was used to obtain aggregate-size classes. The soil samples were dry-sieved through a nested sieve using a mechanical sieve shaker to obtain the following aggregate-size classes: 4.75-2, 2-1, 1-0.5, 0.5-0.25, and 0.25 mm. Soil organic carbon (SOC) concentration in different aggregate-size classes was determined via the acid dichromate wet-oxidation procedure (Nelson & Sommers, 1996). The carbohydrate (R-CHO) concentration in dry-aggregate size classes was determined by the phenol-sulphuric acid hydrolytic extraction procedures, using 10ml of 0.25 M H<sub>2</sub>SO<sub>4</sub>.

### 2.6. Determination of Aggregate Stability

Water-stable aggregates (WSA) were measured by the wet-sieved (slaking pre-wet) process (Nimmo & Perkins, 2002), using 50 g of the 4.75 mm dry aggregates. The mean weight diameter (MWD) of water-stable aggregates was calculated by the equation:

$$MWD = \sum_{i=1}^n x_i \times w_i \quad [8]$$

where xi is the mean diameter of each aggregate size fraction, and wi is the weight of aggregates in that size range.

### 2.7. Statistical analysis

Statistical analyses of the data were performed using the SAS software (SAS Institute, 2016). Analysis of variance was performed, followed by multiple comparisons. Means were separated according to the least significant difference of Fisher's protected test. A significant correlation coefficient was tested at 5% probability.

## 3. RESULTS

### 3.1. Soil texture, bulk density, and porosity

The soil is sandy loam at 0-15 cm and sandy clay loam at 15-30 cm depths. Sand content is between 812 g kg<sup>-1</sup> and 817 g kg<sup>-1</sup> at 0-15 cm and 721 g kg<sup>-1</sup> and 733 g kg<sup>-1</sup> at 15-30 cm depth (Table 2). Clay content ranged between 68 g kg<sup>-1</sup> at 0-15 cm and 162 g kg<sup>-1</sup> at 15-30 cm depths. Significant statistical difference was obtained for bulk density in Alchornea soil (p<0.05). Bulk densities were 1.37, 1.45, 1.50, and 1.51 g cm<sup>-3</sup> for Alchornea, Rubber, Oil palm, and Teak, respectively, at 0-15 cm topsoil. In Table 2, total porosity was significantly higher (p<0.05) at 0-15 cm for Alchornea soil at 48.3% in comparison to 45.3, 43.4, and 43% for Rubber, Oil palm, and Teak, respectively. At 15-30 cm depth, total porosity was also significantly higher (p<0.05) at 47.9% for Alchornea compared to 41.1% for Rubber, 43% for Oil palm, and 40.4% for Teak. Macro-porosity (pores <5 μm) was higher at 28.6% for Alchornea at 0-15 cm and 17.2% at 15-30 cm depths (Table 2). Alchornea plant significantly increased the macro-porosity by 22%, 133%, and 151%, compared to Rubber, Oil palm, and Teak, respectively.

### 3.2. Hydraulic conductivity, water holding capacity and organic carbon stock

In Table 3, saturated hydraulic conductivity (Ksat) was significantly influenced by land-uses (p < 0.05). The highest Ksat value of 48.4 cm h<sup>-1</sup> was obtained for Alchornea at 0-15 cm, followed by 26 cm h<sup>-1</sup> for Rubber and 19.3 and 12.2 for Oil palm and Teak (Table 3). Permeability was rapid and moderately rapid for Alchornea and Rubber, while moderately slow for Oil palm and Teak soils. Ksat values of 19.3 and 12.2 cm h<sup>-1</sup> were obtained at 0-15 cm for Oil palm and Teak soils. Water holding capacity (WHC) at 0-15 cm was significantly higher (p < 0.05) in Alchornea soils at 0.27 g g<sup>-1</sup>, whereas, Oil palm, Teak, and rubber showed a non-significant difference in WHC of the soil (Table 3). Soil organic carbon stock (SOCS) at 0-15 cm soil was 77.7 kg ha<sup>-1</sup> in Alchornea, 81.8 kg ha<sup>-1</sup> in Rubber, 92.2 kg ha<sup>-1</sup> in Oil palm and 67.5 kg ha<sup>-1</sup> in Teak soils. At 15-30 cm depth, the lowest value of 39.3 kg ha<sup>-1</sup> was obtained in Teak soil, compared to 76.2, 74.9, and 60.7 kg ha<sup>-1</sup> found in Alchornea, Rubber, and Oil palm soils, respectively.

**Table 2.** Texture, bulk density and porosity of the soils under the various land use

Land use	Sand (g kg <sup>-1</sup> )	Silt (g kg <sup>-1</sup> )	Clay (g kg <sup>-1</sup> )	Texture	BD (g cm <sup>-3</sup> )	%Macro porosity (>5 µm)	%Micro porosity (<5µm)	Total porosity (%)
<b>0-15 cm</b>								
Alchornea	817a	108b	75a	SL	1.37b	28.6a	19.7b	48.3a
Rubber	815a	110b	75a	SL	1.45a	23.5a	21.8b	45.3b
Oil palm	812a	120a	68a	SL	1.50a	12.3b	31.1a	43.4b
Teak	815a	109b	76a	SL	1.51a	11.4b	31.6a	43.0b
<b>15-30 cm</b>								
Alchornea	721a	131a	148a	SCL	1.38b	17.2a	30.7a	47.9a
Rubber	722a	122a	156a	SCL	1.56a	13.2b	27.9a	41.1b
Oil palm	719a	119a	162a	SCL	1.51a	9.9b	33.1a	43.0b
Teak	733a	119a	148a	SCL	1.58a	10.1b	30.3a	40.4b

**Note:** Means followed by the same letter in each column for each depth for each parameter are not significantly different at  $p < 0.05$ . BD- bulk density, SL- sandy loam, SCL- sandy clay loam.

**Table 3.** Hydraulic conductivity, water holding capacity, aggregate stability and organic carbon stock

Land use	Ksat (cm hr <sup>-1</sup> )	WHC (g g <sup>-1</sup> )	SOCS (kg m <sup>-2</sup> )	Permeability Class
<b>0-15 cm</b>				
Alchornea	48.42a	0.27a	77.7b	Rapid
Rubber	25.98b	0.21b	81.8b	Moderately rapid
Oil palm	19.30b	0.21b	92.2a	Moderately slow
Teak	12.2c	0.21b	67.5c	Moderately slow
<b>15-30 cm</b>				
Alchornea	20.23a	0.22a	76.2a	Moderately rapid
Rubber	18.75a	0.21a	74.9a	Moderately slow
Oil palm	12.72b	0.21a	60.7b	Moderately slow
Teak	12.54b	0.23a	39.3c	Moderately slow

**Note:** Means followed by the same letter in each column for each depth for each parameter are not significantly different at  $p < 0.05$ . Ksat- saturated hydraulic conductivity, WHC- water holding capacity, SOCS- soil organic carbon stock.

### 3.3. Water stable aggregates and aggregate stability

Water stable aggregates showed significant enhancement of large aggregates  $WSA_{2-1\text{ mm}}$  in Alchornea soil at 0-15 cm (Table 4). Smaller macro-aggregates  $WSA_{0.5-0.25\text{ mm}}$  was significantly higher ( $p < 0.05$ ) in Teak and Rubber soils at 28 and 26%. At 15-30 cm depth, smaller macro-aggregates  $WSA_{0.5-0.25\text{ mm}}$  were 31% in oil palm, 30.5% for Rubber and Teak, and 28% for Alchornea. In general, macro-aggregates  $\geq 0.25\text{ mm}$  summed up to 75.5, 71.5, 70.0, and 75% of the total soil mass in Alchornea, Rubber, Oil palm, and Teak, respectively, at 0-15 cm, indicating general structural enhancement of the soils. Micro-aggregates  $< 0.25\text{ mm}$  were generally low in all the soils, with the lowest value of 18.5% obtained in Rubber soil at 0-15 cm topsoil, and 17% for Alchornea at 15-30 cm soil.

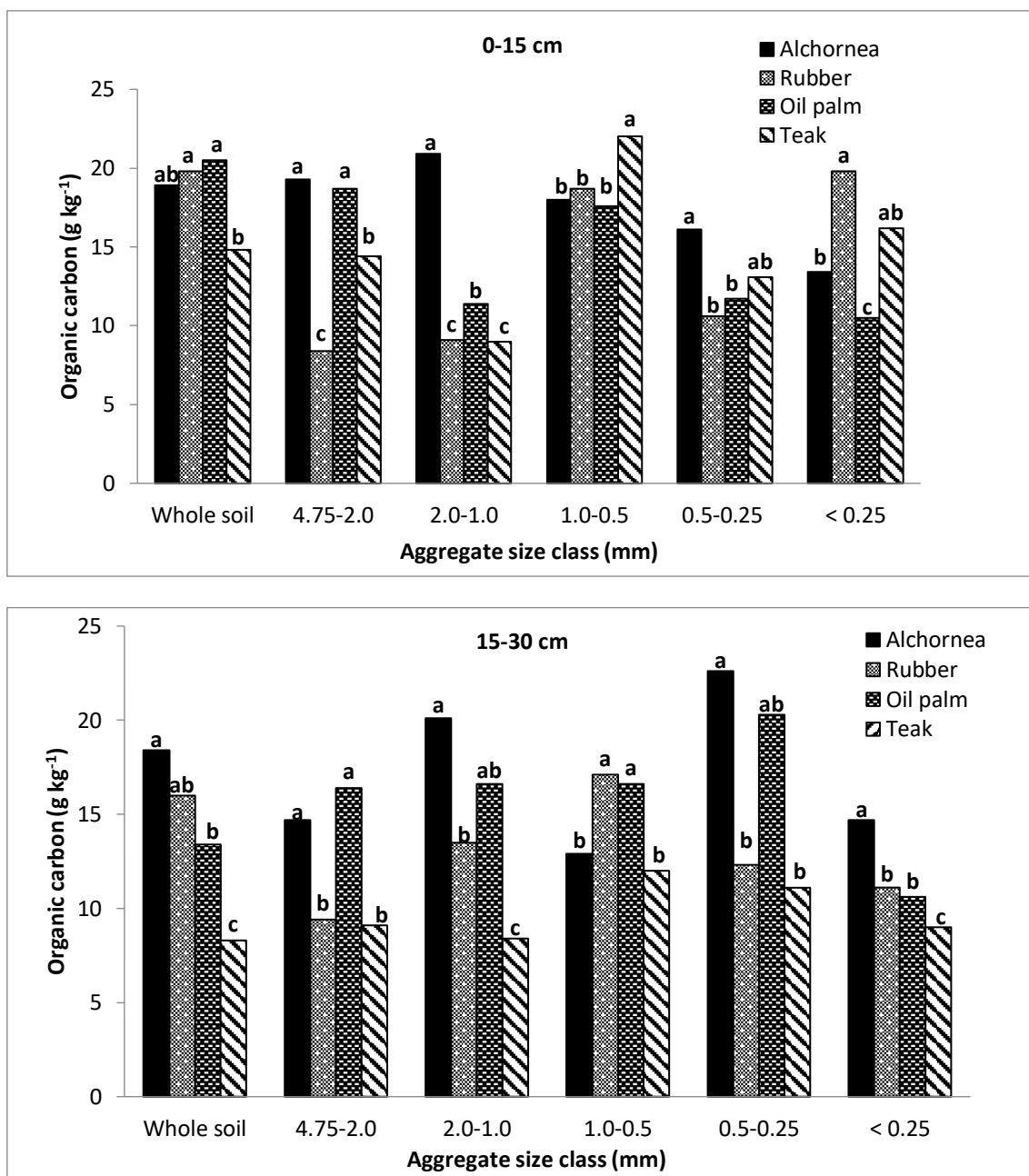
Aggregate stability measured by the mean weight diameter (MWD) of water-stable aggregates in Table 4 showed significant differences due to land use, with Alchornea soil having the highest in MWD of 1.01 mm, compared to 0.89 mm found in Teak soil at 0-15 cm topsoil. The lowest MWD of 0.77 mm was obtained for Oil palm soil at 15-30 cm depth (Table 4). In general, the MWD values indicated the dominance of the less erodible aggregates.

### 3.4. Aggregate-associated soil organic carbon

Soil organic carbon (SOC) in bulk soils and aggregate-size classes showed significant differences due to land use (Figure 1). At 0-15 cm, SOC concentration in the bulk soil was highest in Oil palm and Rubber (20.5 and 19.8 g kg<sup>-1</sup>). This was followed by 18.9 g kg<sup>-1</sup> in Alchornea and the lowest value of 14.8 g kg<sup>-1</sup> found in Teak. At 15-30 cm SOC concentrations in bulk soils were 18.4, 16.0, 13.4, and 8.3 g kg<sup>-1</sup> for Alchornea, Rubber, Oil palm, and Teak, respectively. When compared to values obtained at 0-15 cm, SOC decreased by 18.4%, 16.0, 13.4, and 78.3%, respectively, in bulk soils for Alchornea, Rubber, Oil palm, and Teak. Results also revealed that >65.8% of SOC was protected in macro-aggregates  $> 0.5\text{ mm}$  in Alchornea soils, compared to less than 45.1% in similar aggregate-size classes in Rubber, Oil palm and Teak soils (Figure 1). Alchornea and Oil palm soils stored 20.1 g kg<sup>-1</sup> of SOC in 2.0-1.0 mm aggregate-size class and 22.6 g kg<sup>-1</sup> in 0.5-0.25 mm aggregates at 15-30 cm depth. Generally, greater SOC was protected in macro-aggregates  $> 0.5\text{ mm}$  in Alchornea and Oil palm soils.

### 3.3. Aggregate-associated carbohydrates

Acid-hydrolyzable carbohydrates (R-CHO) were significantly ( $p < 0.05$ ) higher in the bulk soil and macro-aggregates  $> 0.5\text{ mm}$  in Alchornea soils (Fig. 2). At 0-15 cm, R-CHO concentration in bulk soil was in the order of Alchornea > Rubber > Oil palm > Teak. The highest acid-hydrolyzable carbohydrates of 12.5 g kg<sup>-1</sup> were stored in 4.75-2 mm aggregate-size class in Alchornea soil at 0-15 cm topsoil and 15-30 cm depth. For instance, aggregate-associated acid-hydrolyzable carbohydrate concentrations in 4.75-2.0 mm aggregate-size class were 12.5 g C kg<sup>-1</sup> for Alchornea, followed by 9.8 g C kg<sup>-1</sup> in 0.5-0.25 mm for Oil palm soils at 15-30 cm depth.



**Figure 1.** Distribution of soil organic carbon in whole soil and dry-aggregate sizes under different land use at 0-15 cm and 15-30 cm. Columns followed by the same letters for each aggregate size class for each depth are not significantly different at  $p < 0.05$

**Table 4.** Water stable aggregates and aggregate stability of soil under different tree land use

Land use	5-2 mm	2-1 mm	1-0.5 mm	0.5-0.25 mm	< 0.25 mm	MWD (mm)
<b>0-15 cm</b>						
Alchornea	12.0a	17.0a	27.0b	19.5b	24.5b	1.01a
Rubber	9.5a	13.0b	33.0a	26.0a	18.5c	0.92a
Oil Palm	11.0a	12.0b	29.0b	20.0b	28.0a	0.92a
Teak	9.5a	14.0b	23.5c	28.0a	25.0b	0.89a
<b>15-30 cm</b>						
Alchornea	11.5a	14.5a	29.0a	28.0a	17.0b	0.99a
Rubber	10.0a	12.0b	28.0a	30.5a	19.5b	0.91a
Oil Palm	5.0b	15.5a	24.5b	31.0a	24.0a	0.77b
Teak	10.0a	15.0a	20.0c	30.5a	24.5a	0.91a

**Note:** Means followed by the same letters for each aggregate size class for each depth are not significantly different at  $p < 0.05$ , MWD- mean weight diameter.

In general, aggregate-associated acid-hydrolyzable carbohydrates were in the order of 4.75-2.0 > 2.0-1.0 > 1-0.5 mm for Alchornea and Oil palm soils. The major contrast in aggregate-associated R-CHO and SOC was that greater R-CHO was stored in smaller aggregates < 0.25 mm in the subsoil, while greater SOC was specially protected in larger aggregates 4.75-2.0 and 0.5-0.25 mm in 0-15 cm topsoil.

### 3.5 Relationships amongst related soil properties

Correlations among soil properties revealed a significant positive linear correlation between MWD and R-CHO and SOC, accounting for 62.9 and 62.2% of the relationships, respectively (Table 5). A highly significant positive correlation was found between MWD and Ksat ( $r = 0.867$ ,  $p < 0.01$ ), which explained 75.2% of the positive variation. A non-significant linear correlation between Ksat and R-CHO ( $R = 0.466$ ,  $p > 0.05$ ), showed that SOC more than carbohydrates influenced the saturated hydraulic conductivity. Positive correlation between Ksat and SOC ( $r = 0.784$ ,  $p < 0.05$ ), accounted for 61.5%, while significant positive correlation between WHC and MWD accounted for 64.2% of the relationship ( $r = 0.801$ ,  $p < 0.05$ ), following an increase in Ksat and saturation water content of the soil (Table 5). Clay content showed significant positive linear correlation with R-CHO ( $r = 0.716$ ,  $p < 0.05$ ), and a non-significant correlation with SOC ( $r = 0.459$ ,  $p > 0.05$ ).

The equation,  $R\text{-CHO} = 0.816 + 1.524(\text{clay})$ , is suitable to predict the positive changes in carbohydrate content in soil depth with an increase or decrease in clay content. Micro-porosity showed a negative relationship with SOC ( $r = -0.625$ ,  $p < 0.05$ ) and a positive linear relationship with R-CHO ( $r = 0.717$ ,  $p < 0.05$ ), which further explained the positive role of clay content on acid-hydrolyzable R-CHO in the soil. The

model,  $\text{macro-porosity} = 1.648 + 2.051(\text{SOC})$  is suitable to predict 67.1% of improvements in macro-porosity with increase in SOC content (Table 5). The correlation between macro-porosity and R-CHO was not significant, accounting for only 25.7% of the relationship ( $r = 0.507$ ,  $p > 0.05$ ). Macro-aggregates >0.25 mm showed a highly positive correlation with SOC ( $r = 0.826$ ,  $p < 0.01$ ), and a non-significant with R-CHO ( $r = 0.531$ ,  $p > 0.05$ ). The relationships between micro-aggregates <0.25 mm and SOC and R-CHO were significant ( $r = 0.747$ ,  $p < 0.05$ ; and  $r = 0.709$ ,  $p < 0.05$ ) respectively, accounted for 55.8% and 50.3%, respectively in the formation of micro-aggregates in the soil.

## 4. DISCUSSION

Soil properties varied significantly in response to land use. The Alchornea reduced the soil bulk density (BD), increased saturated hydraulic conductivity (Ksat) and water holding capacity (WHC). The significant improvement of soil properties due to Alchornea plant could be attributed to the high production of quality organic residues, compared to the relatively low quality from Oil palm, Rubber and Teak. Quality and quantity of SOM from Alchornea bush have been reported to benefit soil physical properties through a reduction in bulk density and increase in the optimum moisture content of sandy loam soil (Udom & Ehilegbu, 2018). The studies of Nweke and Nwabude (2015) also showed that quality rather than quantity of organic matter was responsible for the improvement of physical properties through possible rearrangement of the soil structures. The effect of vegetation on water-stable of aggregates (WSA) and the mean weight diameter (MWD) in this study could be used to explain the extent of soil agglomeration under the tree fallow systems.

**Table 5.** Relationships amongst some structural properties of the bulk soil and SOC, R-CHO, clay content (N=20)

Regression equation	R <sup>2</sup>	R	P
MWD = -2.917 + 0.123(SOC)	0.629	0.793	*
MWD = 2.553 + 0.466(R-CHO)	0.622	0.789	*
MWD = 2.096 + 0.111(Ksat)	0.752	0.867	**
WHC = 1.492 + 2.014(MWD)	0.642	0.801	*
K <sub>sat</sub> = -10.84 + 2.903(R-CHO)	0.217	0.466	NS
K <sub>sat</sub> = 0.862 + 2.486(SOC)	0.615	0.784	*
R-CHO = 0.816 + 1.524(clay)	0.513	0.716	*
SOC = -2.461 + 1.601(clay)	0.249	0.499	NS
Micro-porosity = 0.659 + 1.652(SOC)	0.391	-0.625	*
Micro-porosity = -3.019 + 1.702(R-CHO)	0.514	0.717	*
Macro-porosity = 1.648 + 2.051(SOC)	0.671	0.819	**
Macro-porosity = 0.216 + 2.111(R-CHO)	0.257	0.507	NS
Macro-aggregates >0.25 mm = 2.131 + 0.892(SOC)	0.682	0.826	**
Macro-aggregates >0.25 mm = -2.726 + 2.512(R-CHO)	0.281	0.531	NS
Micro-aggregates < 0.25 mm = 0.792 + 1.601(R-CHO)	0.503	0.709	*
Micro-aggregates <0.25 mm = -1.812 + 0.151(SOC)	0.558	0.747	*

**Remarks:** R<sup>2</sup>–Coefficient of determination, R – Coefficient of correlation, SOC – Soil organic carbon, MWD –Mean weight diameter, Ksat – Saturated Hydraulic conductivity, WHC- water holding capacity, R-CHO – Carbohydrate, \*Significant at  $p < 0.05$ , \*\*Significant at  $p < 0.01$ .

Alchornea and Oil palm increased the macro-aggregate size classes 4.75-2.0 and 2.0-1.0 mm compared to Rubber and Teak, most probably supporting the quality of soil organic matter produced from Alchornea plants. This accession further confirmed the findings of Zhao et al. (2017) that the quality and quantity of SOM in a forest ecosystem were responsible for the production of macro-aggregates and stable structures in tropical sandy loam soil. The agglomeration of smaller aggregates into larger aggregates in Alchornea and Oil palm soils can be added to the SOM content in conjunction with the possibility of expansive activities of micro-organisms in the soil. Aggregate stability expressed by the MWD of water-stable aggregates reflected the proportion of larger aggregates produced in Alchornea soil, and consistent with studies of Devine et al. (2014); Liu et al. (2014), and Zhang et al. (2019) who found

had an increase in production of macro-aggregates >2.0 mm and large MWD due to organic residues added to the soil through the vegetation.

Soil organic C stored in macro-aggregates >0.25 mm was highest in Alchornea and Oil palm soils, which further confirms the works of Yu et al. (2012) and Abdelrhman et al. (2021) who found the encrustation of SOC in macro-aggregates as a physical protective mechanism for soil aggregate against losses during disruption and erosion. The increase in acid-hydrolyzable carbohydrates in macro-aggregates of Alchornea and Oil palm soils can also be used to suggest the improvement in soil aggregation under the Alchornea bush. However, other findings had differed in the conclusion that carbohydrates cannot always be considered as persistent structural stabilizers because of their rapid degradation by microbial activity (Udom & Simon, 2020).

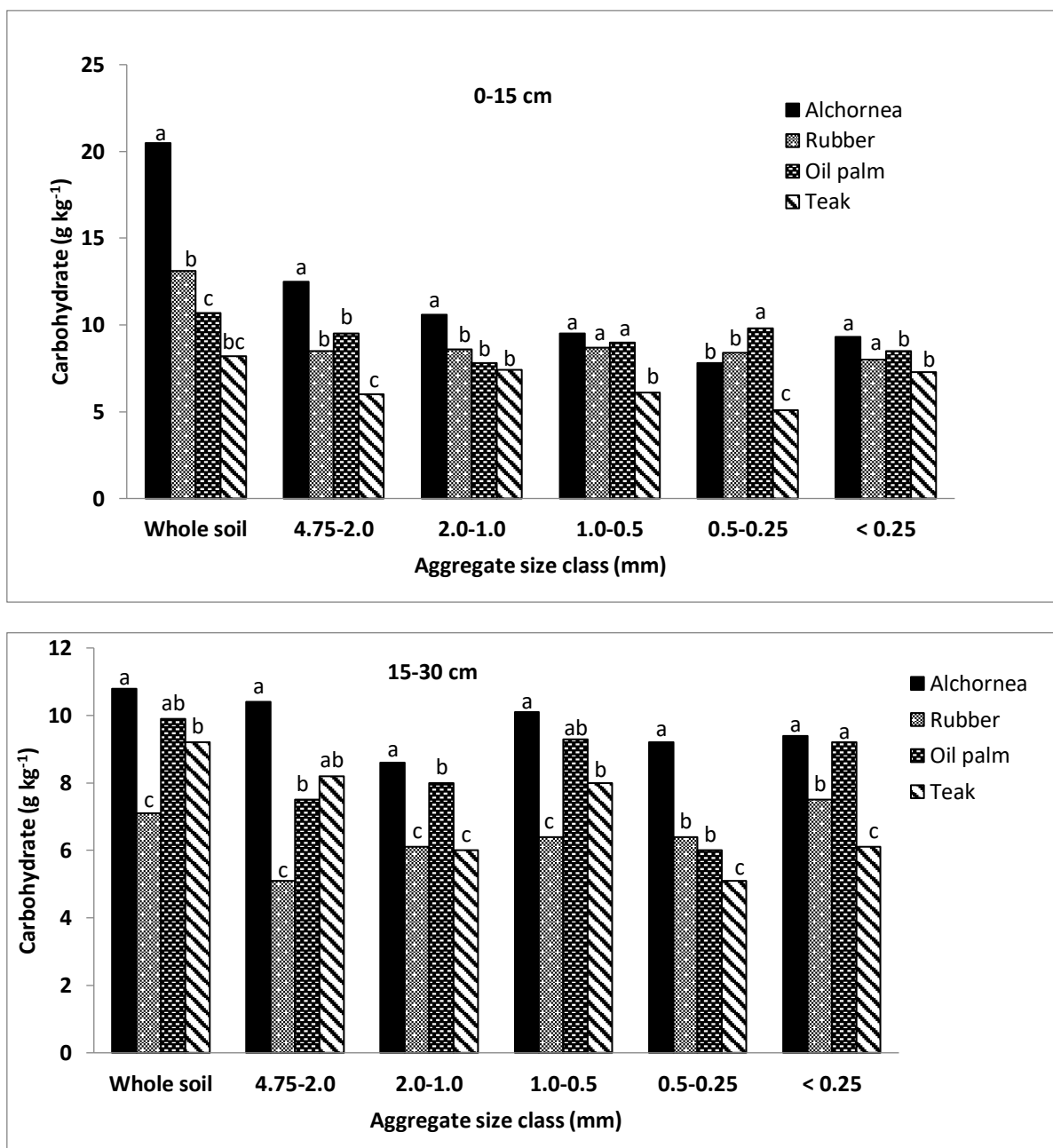


Figure 2. Distribution of carbohydrate (R-CHO) in whole soil and dry aggregate size class under different land use at 0-15 cm and 15-30 cm. Columns followed by the same letters for each aggregate size class for each depth are not significantly different at p<0.05.

It is also possible to argue that the high carbohydrates and SOC found in Alchornea and Oil palm soils compared with the Rubber and Teak would have potentially rejuvenated the soil hydraulic and structural properties reported in Tables 1 and 2. This may further support the findings of Parwada and Van Tol (2017) that acid-hydrolyzable carbohydrate fractions alone did not improve macro-aggregate stability rather, the other components of organic matter such as the humified fractions of the SOM. A large amount of acid-hydrolyzable carbohydrates stored in micro-aggregates <0.25 mm at 15-30 cm depth was not surprising, because Gupta and Germida (2015) had earlier observed a high amount of acid-hydrolyzable carbohydrates in the subsoil and related it to the activities of micro-organisms during micro-aggregate formation, rather than the amount of decomposable organic residues. This further explained the high amount of SOC in 0-15 cm topsoil may have been involved in the biological stabilization of carbohydrates and protected it from microbial degradation. This result partially confirmed the report of Zubair et al. (2012) that acid-hydrolyzable carbohydrates in macro-aggregates and sand-sized particles in this study may have been due to the microbial decomposition of organic residues from Alchornea. Further, it could be argued that the microbial-derived sugars in the plant residues may have accounted for a large proportion of carbohydrates stored in micro-aggregates, consistent with the studies of Xiao et al. (2017) and Udom and Benwari (2018) who found an increase in population and activities of bacteria in clay-sized fractions of tropical sandy loam soil. This way, it could be postulated that the preferential storage of acid-hydrolyzable carbohydrates in the clay-size micro-aggregates was most probably due to the increase of biological activities in clay-sized particles.

Relationships showed a positive linear correlation of MWD with SOC and acid-hydrolyzable carbohydrates (R-CHO) confirming the positive roles of SOC and R-CHO as aggregating agents when in association with soil aggregates (Zubair et al., 2012). Similarly, the positive correlation between MWD and K<sub>sat</sub> confirmed the crucial role of SOC in relation to the structural stability of soil and to a large extent, the aeration capacity and water movement into and within the soil. The significant linear model between SOC and clay content is consistent with the earlier findings of Yu et al. (2012) who found that SOC was more stable in silt-clay fractions and within micro-aggregates. Also, the positive correlation between acid-hydrolyzable R-CHO and micro-porosity further confirmed that acid-hydrolyzable R-CHO was more closely related to micro-porosity and contributed little to the percolation porosity as earlier reported by Zhang et al. (2016). The positive correlations of SOC and R-CHO with micro-aggregates tended to further explain the involvement of SOC and R-CHO in the stabilization of micro-aggregates, consistent with the report of Ratnayake et al. (2013). On the other hand, the non-significant correlation between R-CHO and macro-aggregates in tandem with the findings of Martins et al. (2012), who found that the carbohydrate pool did not promote macro-aggregate stability, rather the SOC and humic fractions of SOM that was responsible for the formation of macro-aggregates

## 5. CONCLUSIONS

Alchornea bush and Oil palm plantation reduced bulk density, increased total porosity and saturated hydraulic conductivity of the soils. They also increased the formation of macro-aggregates >0.25 mm. Soil organic C was preferentially stored in larger aggregate size classes 4.75-2.0 mm and 2.0-1.0 mm in Alchornea and Oil palm soils. Acid-hydrolyzable carbohydrates and SOC showed a significant positive correlation with the MWD, while R-CHO showed a positive relationship with micro-aggregates. A linear model showed that SOC controlled macro-porosity through an increase in saturated hydraulic conductivity (K<sub>sat</sub>). Acid-hydrolyzable carbohydrates had a non-significant effect in the formation of macro-aggregates >0.25 mm. The clay-size fraction most predicted the amount of carbohydrates under the tree fallow cultures. Alchornea and Oil palm fallow cultures increased macro-aggregate stability and boost the protection of SOC and R-CHO within soil aggregates.

## Declaration of Competing Interest

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

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