

COMPARATIVE ASSESSMENT OF SOIL PROPERTIES UNDER OIL PALM MONOCULTURE AND OIL PALM-COCOA INTERCROPPING SYSTEMS

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ABSTRACT

The economic viability of cocoa and its shade-loving character made it a successful intercrop in oil palm (OP) plantations. However, its effect on soil properties, especially physical properties, is not fully understood in OP based cropping system. Two cropping systems (OP monoculture and OP + cocoa intercropping) at two sampling points (basins and interspace) and five soil depths (0–20, 20–40, 40–60, 60–80 and 80–100 cm) were considered in the study. This investigation sought to quantify the effects of intercropping in OP plantations on bulk density, aggregate stability, total organic carbon (TOC), total nitrogen (TN), glomalin-related soil protein (GRSP), aggregate-associated TOC, TN and carbon preservation capacity (CPC) of the aggregate fractions. Compared to OP monoculture, cocoa intercropping in OP plantations significantly improved the geometric mean diameter (GMD) of the aggregates by 12.70%–64.00%, aggregate stability index (ASI) by 9.87%–24.00%, TOC by 6.80%–49.70%, TN by 3.00%–28.10% and GRSP by 11.80%–54.60%. Under intercropping, the TOC and TN contained in different aggregate fractions also improved. Small macroaggregate fractions were the aggregate fractions with the greatest capacity to store carbon (3.27–16.60 g kg⁻¹). Furthermore, intercropping increased the CPC of the soil aggregates, particularly micro and macroaggregates, by 1.88%–71.00%. The study suggested that intercropping cocoa in OP plantations is a sustainable strategy to enhance soil health and maximise carbon sequestration.

Keywords: aggregate stability, cocoa, intercrop, oil palm plantations.

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INTRODUCTION

Oil palm (OP) cultivation in India has gained significant momentum due to increasing efforts and policy support from the government, primarily through the launch of specific schemes like National Mission on Edible Oils - Oil Palm (NMEO-OP). The length of time (about 3 to 4 years) required for the OP to begin producing fresh fruit bunches is a significant issue, particularly for smallholders (Nchanji et al., 2016). As the equilateral triangle method (9 x 9 x 9 m) of planting is practised, only 5%–15% of the area is covered during the juvenile

phase (Suresh & Rethinam, 2001) and 35%–40% of the area remains covered in mature OP plantations (Gawankar et al., 2018), enabling the scope of intercrops. Intercropping is widely supported and practised in OP cultivation, especially during the juvenile phase, to provide farmers with income, food security and reduced costs while improving soil health by growing suitable food crops like legumes, vegetables and some tubers in the spaces between young palms (Dissanayake & Palihakkara, 2024). Intercropping is a sustainable practice that maximises land use before the palm matures (Okyerere et al., 2014), but requires careful selection of non-competitive crops and proper spacing to avoid harming the palms. Monocropping of OP in tropical peatlands for two generations is reported to increase the bulk density and carbon losses (Dhandapani et al., 2019). Intercropping is found

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to be an environmentally wise alternative even in such peatlands (Dhandapani et al., 2020).

Intensive agricultural practices like over-tillage, monocropping and excessive chemical use were reported to degrade the soils unsustainably (Kopittke et al., 2019). Intercropping is a key mitigation strategy that restores soil health, increases resource use efficiency and promotes sustainability (Yeboah et al., 2026). In northeastern parts of India, planting pineapple as an intercrop improved the OP yield and carbon (C) stock compared to OP monoculture (Ahirwal et al., 2022). Integrating other crops with OP enables improved habitat for the associated microbes and increases the nutrient supply by releasing it from their fixed forms (Belel et al., 2014; Buragohain, 2015). In the Konkan region of Maharashtra, intercropping (banana, elephant yam and pineapple) in OP triggered the OP yield by 36.40% compared to its monoculture (Gawankar et al., 2018). Intercropping in OP with cassava and sorghum improved soil biological activity (bacterial and fungal count) (Sapalina et al., 2022). Contradictorily, Koussihouèdé et al. (2020) reported potassium deficiency in soils of OP plantations with cassava, maize, pineapple and tomato intercropping. Similarly, Pérez-Sato et al. (2023) reported a declining soil fertility status with increasing palm age. Suitability of the intercrop depends on the age of the OP plantation. As the palm ages, its roots entwine, resulting in nutrient competition, soil compaction and crop root strangulation (De Oliveira et al., 2022). Research indicates that some commercial plants are unable to flourish in OP due to the canopy cover's poor light transmission to the soil surface (Akinde et al., 2020). Shade-tolerant crops like banana, cocoa, black pepper, long pepper, malabar neem, coffee, pineapple, fodder crop, heliconia, red ginger and ornamental crops (fish tail fern, dieffenbachia, philodendra and asparagus) were found to be highly suitable (Ramachandrudu, 2015). Among these, cocoa is the perfect companion crop for OP without reduction in yield of the main crop (Corley & Tinker, 2003). When cocoa is intercropped in OP, a symbiotic association happens, i.e., OP provides shade to cocoa while cocoa adds a lot of organic matter to the OP system. OP has an adventitious root system (Yampolsky, 1924), whereas cocoa has a taproot system (Niether et al., 2019). As they both have different root systems, integrating them results in complementary resource use (water, nutrients and sunlight).

Every year, the cocoa crop contributes between 6 and 8 t of residues to the soil (Sreekala, 1997). The leaf litter from cocoa is an important organic carbon source that improves soil properties (Manorama et al., 2021). This also has an impact on the biogeochemical cycles, which include nutrient cycling, sequestration and C dynamics

(Dislich et al., 2017). Cocoa intercropped in OP was reported to have a high land equivalent ratio, enhanced groundwater replenishment and low C footprint (Khasanah et al., 2020). Adding this, research (Amoah et al., 1995; Bhagya & Suresh, 2018; Narsimha Rao et al., 2019) also showed the growth, economic viability of cocoa and their carbon sequestering potential in OP plantations, but there is still a dearth of published data on soil properties, especially physical properties, under OP based cropping system. We hypothesise that intercropping cocoa in OP plantations could improve the soil properties compared to OP monoculture. Therefore, the objectives of this investigation were to 1) compare the effect of OP with cocoa intercropping and OP monoculture on soil physical properties (bulk density, aggregate stability index [ASI] and geometric mean diameter [GMD]) and glomalin-related soil protein (GRSP), 2) to assess the effect of 17 years of cocoa intercropping on total carbon and nitrogen content in different aggregate fractions; and 3) to evaluate the carbon preservation capacity (CPC) of the aggregates under intercropping and monoculture systems.

MATERIALS AND METHODS

Experimental Details

The study area is the Indian Institute of Oil Palm Research's research farm in Andhra Pradesh, India (16° 48' 49" N, 81° 8' 2" E), with the experimental site occupying a total area of 3,000 m² (0.30 ha). The experimental site has a tropical climate with hot, dry summers from March to June, wet seasons from July to December, and comparatively cool winters. Minimum and maximum temperatures in the area range from 16.9°C to 26.4°C and from 27.7°C to 38.1°C, respectively. According to the United States Department of Agriculture (USDA) soil taxonomy, the soils are categorised as Typic Rhodustalfs and have a sandy loam texture (Soil Survey Staff, 2014). The cropping system treatments include OP monoculture and OP + cocoa intercropping. OP is grown in an equilateral triangular system of planting (9 × 9 × 9 m). Twelve-month-old planting material of *Dura* × *Pisifera* crosses was planted during October 1995. Basins were formed, and the fronds cut during each harvest were applied as mulch in basins to conserve soil moisture. For cocoa intercropping in OP treatments, cocoa was planted in the middle of two rows of OP during August 2007, and the distance between cocoa plants in a row was 3 m. Cocoa seedlings of six months were planted. Every year, pruning was done during August or September to ensure adequate ventilation. The pruned OP fronds (7.2 t ha⁻¹ yr⁻¹) and cocoa litter (2.5 t ha⁻¹ yr⁻¹) were recycled within

the system. Pruned fronds of OP were applied as mulch in OP basins. Drip irrigation along with soil application of the recommended dose of fertilisers is followed. The planting pattern is depicted in Figure 1.

Soil Sampling

Soil samples were collected during April 2025 from the OP basin and interspace region. Samples from the basins were taken 1.5 m from the palm base. In OP with cocoa intercropping, interspace samples were collected 60 cm from the base of the cocoa tree, while in OP monoculture, samples were taken between two rows of OP (3.9 m away from the palm base). Soils from 0 to 100 cm depth were taken from each sampling point (0–20, 20–40, 40–60, 60–80 and 80–100 cm). To determine the bulk density, core soil samples of 100 mm in height and 80 mm in diameter were collected from each soil depth. In total, 60 soil samples were taken from three replicates, two locations, five depths and two cropping systems. After removing the roots and debris, soils were prepared according to the standard procedure established by the Food and Agriculture Organization of the United Nations (FAO, 2019) and further stored in airtight containers.

Soil Analysis

The core method (Blake & Hartge, 1986) was used to determine the soil's bulk density. Soil aggregate distribution was determined by the wet sieving method outlined by Mangalassery et al. (2019). Evenly dried soil samples (<4.000 mm) were categorised into silt + clay (<0.053 mm),

microaggregates (0.053–0.250 mm), small macroaggregates (0.250–2.000 mm) and large macroaggregates (>2.000 mm) (Márquez et al., 2004). The GMD of the aggregates and ASI were calculated as follows in Equation (1) and (2).

$$\text{GMD} = \exp \left[\frac{\sum_{i=1}^n P_i \times \log D_i}{\sum_{i=1}^n P_i} \right] \quad (1)$$

where, n is a number of aggregate size fractions, D_i is a mean diameter of the i -th aggregate size, P_i is the proportion of aggregate of the i -th size, and i represents <0.053, 0.053–0.250, 0.250–2.000, or >2.000 mm.

$$\text{ASI} = \frac{(A_i - B_i) \times 100}{A_i} \quad (2)$$

where, A_i is the weight of the sample used for aggregate analysis, and B_i is the weight of the aggregates less than 0.053 mm.

Total C and N concentrations in the soil samples were ascertained by following the dry combustion method using a CN analyser (Vario EL cube, Elementar, Germany) at 950°C (Nelson & Sommers, 1982). A soil sample weighing between 20 and 30 mg was placed in a silver boat. After that, the boat was put inside a quartz ladle that was exposed to the high temperature and oxygen atmosphere within the sample combustion zone. The resulting carbon dioxide and molecular nitrogen were swept into the detector and measured. The inorganic carbon in the soil samples was determined by the rapid titration method given by Rowell (1994). Total soil carbon was regarded as equivalent to total organic carbon (TOC) in the experimental

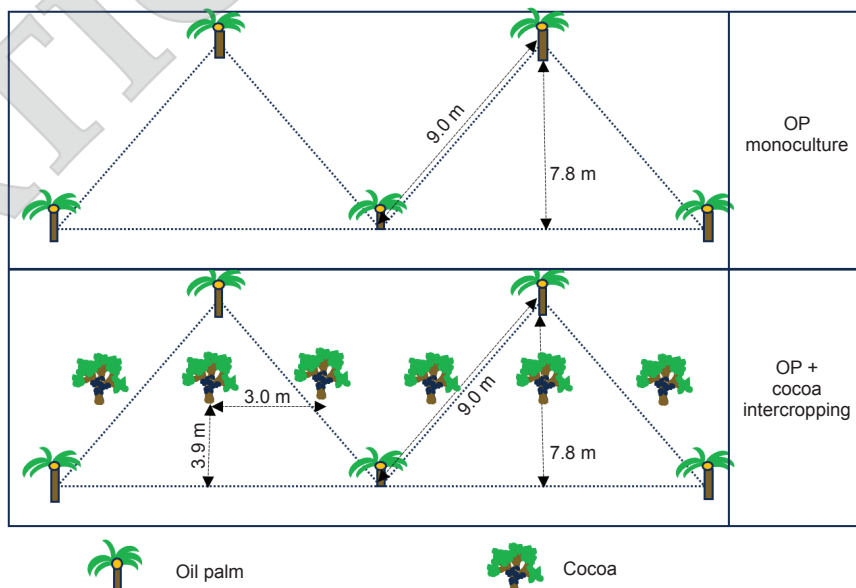


Figure 1. Planting pattern followed in oil palm (OP) monoculture and OP with cocoa intercropping.

soils because the inorganic carbon concentration (carbonates) was nearly zero. After soil aggregate fractionation, samples in each aggregate size class were dried, and TOC and total nitrogen (TN) content were determined as mentioned above. The methodology outlined by Wright and Upadhyaya (1998) was used to determine the GRSP content. One gram of air-dried soil sample was taken in 25 mL tubes, and 8 mL of 20 mM sodium citrate buffer with pH 7.0 was added and mixed well. The tubes were autoclaved at 121°C for 30 min, followed by cooling and centrifugation (10,000 rpm for 10 min). Bovine serum albumin (54156 G10, SDFCL, India) was used as a standard, and the absorbance was measured at 595 nm in a UV-visible spectrophotometer (UV 1900i, Shimadzu, Japan).

Carbon preservation capacity (CPC) of the aggregates was calculated by Equation (3).

$$\text{CPC} = \frac{\text{OC}_i \times W_i}{100} \quad (3)$$

where, OC_i is the total organic carbon content in the aggregate of the i -th aggregate size, W_i is the mass of aggregates of the i -th size, and i represents <0.053, 0.05–0.25, 0.25–2.00 or >2.00 mm.

Statistical Analysis

Three-way analysis of variance (ANOVA) was done with the analytical software program SPSS 16.0 (SPSS Inc., USA) to examine the bulk density, GMD, ASI, GRSP content, TOC and TN associated with aggregates, and CPC under OP monoculture and OP + cocoa intercropping at various soil depths. To ascertain the significant levels of the parameter differences across OP based cropping systems at $p \leq 0.05$, Duncan's multiple range test was employed (Duncan, 1955). The association between the soil properties was determined using Pearson's correlation analysis.

RESULTS AND DISCUSSION

The cropping system, sampling location and depth had a substantial impact on soil bulk density (Table 1). The bulk density of the soils varied from 1.24 to 1.66 Mg m⁻³. It increased with increasing soil depth. Lower bulk density in the top layer (0–20 cm) could be attributed to higher soil organic matter (SOM) content and soil aggregation (Garcia-Orenes, 2005; Li et al., 2024). When the sampling point is taken into account, basins recorded low bulk density compared to the interspace. At 0–20 cm, OP basins in cocoa intercropping recorded low bulk density followed by the interspace. At other soil

depths (20–100 cm), OP basins in cocoa intercropping treatments recorded a low bulk density followed by OP basins in monoculture. Low bulk density in the basin corresponds to higher organic matter additions (Logsdon & Karlen, 2004) through incorporation of pruned OP fronds. Manorama et al. (2021) reported a biomass generation of 15–17 t ha⁻¹ in matured OP plantations and its addition through mulching of palm circles. Higher organic matter additions resulted in higher soil aggregation, which led to lower bulk density as the aggregates create more pore space and better soil structure, reducing compaction (Sadiq et al., 2025). OP plantations with cocoa intercropping recorded a significantly lower bulk density compared to their monoculture. This might be due to a higher proportion of biomass addition by cocoa plantations. Sreekala (1997) reported that the cocoa crop adds 6–8 t of residues to the soil each year. A low bulk density of 1.24 Mg m⁻³ was found in basins of OP plantations intercropped with cocoa at 0–20 cm, whereas the highest bulk density was noted in the interspace of OP monoculture at 80–100 cm. Cocoa trees planted as an intercrop act as a food source (litter and root exudates) and support diverse soil microbial communities and fauna, which play a vital role in soil aggregation and organic matter decomposition, processes that contribute to lower bulk density. Supporting this, Mangalassery et al. (2019) reported the biotic influence of cashew trees on soil aggregation.

Regression analyses were employed to investigate the association between soil bulk density and other soil parameters. Bulk density showed linear relationships with GMD, ASI, TOC and GRSP in the soils of different OP based cropping systems (Figure 2). These results suggest that soils with higher aggregate stability (GMD, ASI), TOC and GRSP content had lower bulk density.

The ability of soil aggregates to withstand changes in their external environment and maintain their stability is determined by soil aggregate stability. It can be measured through GMD and ASI. The GMD of soil aggregates is a crucial indicator of soil health, reflecting aggregate stability, soil structure and fertility. The cropping system and sampling location had a significant impact on the GMD of the aggregates (Figure 3a). GMD of the aggregates ranged from 0.21 to 0.87 mm. The GMD of aggregates declined with soil depth regardless of the cropping system and sampling location. The depletion in SOM could be the possible cause for such reduction. Maximum values were documented in basins of OP + cocoa intercropping at 0–20 cm depth, followed by OP monoculture basins (0.70 mm). Cocoa intercropping improved the GMD in the range of 24.8%–30.3% in OP basins and 12.7%–64.0% in interspaces. Addition of leaf residues in higher quantities in OP + cocoa

TABLE 1. BULK DENSITY OF SOILS UNDER DIFFERENT OIL PALM-BASED CROPPING SYSTEMS

Soil depth	OP monoculture		OP + cocoa intercropping	
	OP basin (Mg m^{-3})	Interspace (Mg m^{-3})	OP basin (Mg m^{-3})	Interspace (Mg m^{-3})
0–20 cm	1.29 ^l	1.32 ^k	1.24 ⁿ	1.27 ^m
20–40 cm	1.34 ^j	1.40 ^h	1.32 ^k	1.38 ⁱ
40–60 cm	1.44 ^f	1.51 ^e	1.37 ⁱ	1.43 ^g
60–80 cm	1.52 ^e	1.60 ^b	1.42 ^g	1.55 ^d
80–100 cm	1.58 ^c	1.66 ^a	1.54 ^d	1.61 ^b

Note: Various lowercase letters indicate significant differences among different cropping systems, sampling locations, and soil depths at $p < 0.05$.

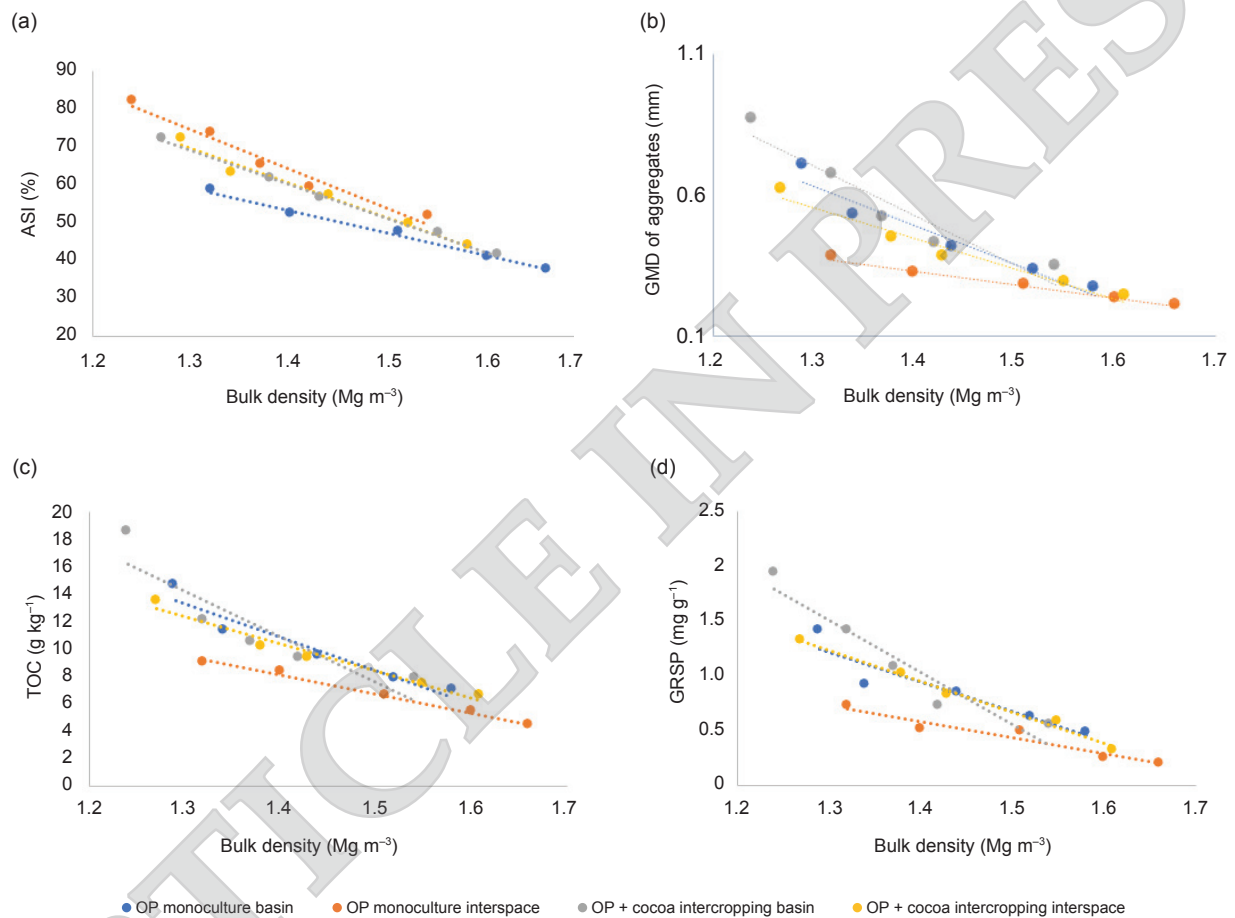


Figure 2. Relationship between bulk density and (a) aggregate stability index (ASI); (b) geometric mean diameter (GMD) of aggregates; (c) total organic carbon (TOC) and (d) glomalin-related soil protein (GRSP).

intercropping could be the possible reason for higher GMD through its positive influence on soil aggregation. Supporting this, Xiao et al. (2022) reported higher soil aggregation and organic matter in soils incorporated with crop residues. Higher GMD of aggregates in the soils of OP basins in cocoa intercropping suggests that retention of crop residues (OP and cocoa) can effectively enhance the particulate SOM inside the aggregates and further increase their size (Sekaran et al., 2021). High GMD

values reflect a greater proportion of large, stable macroaggregates, while lower GMD values indicate a shift towards smaller, less stable microaggregates, which is generally observed in deeper soil layers or areas with low organic matter (Abdelrhman et al., 2025). Supporting this statement, higher ASI was noticed in samples with high GMD. GMD of the aggregates showed a positive linear association with TOC and ASI (Figure 4a and 4b).

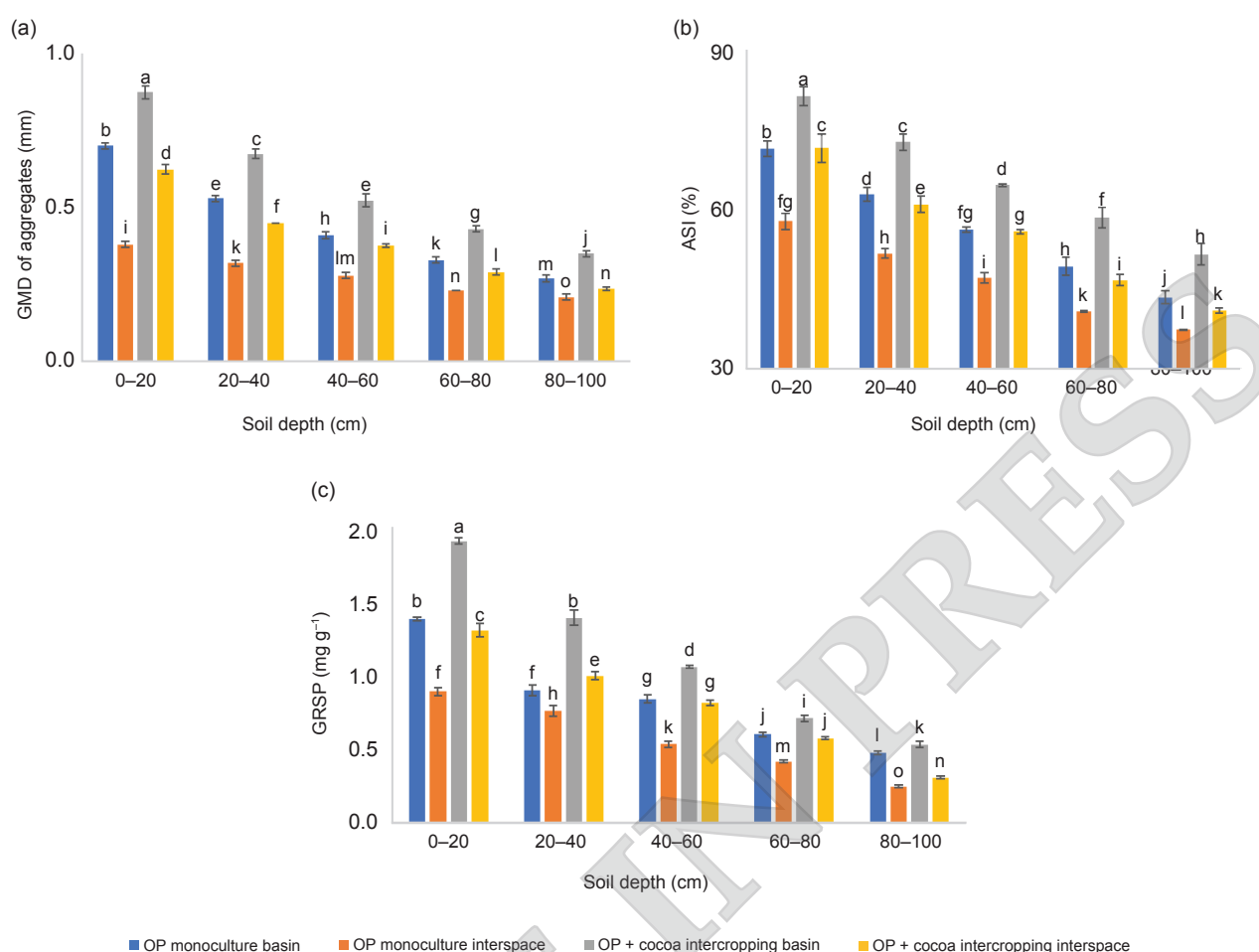


Figure 3. Effect of different oil palm-based cropping systems on (a) geometric mean diameter of aggregates (GMD), (b) aggregate stability index (ASI), and (c) glomalin-related soil protein (GRSP). Various lowercase letters indicate significant differences among different cropping systems, sampling locations, and soil depths at $p < 0.05$.

ASI is significantly influenced by cropping system, sampling point and soil depth. The values ranged between 37.5% and 82.1% (Figure 3b). The ASI values decreased with soil depth. This might be due to a higher concentration of SOM, which supports a higher proportion of aggregates with greater GMD in the top layers (0–20 cm). ASI was increased by 9.87%–24.0% when cocoa was planted as an intercrop in OP plantations. Similarly, basins showed 17.5%–21.4% higher ASI compared to interspace. In this study, introduction of cocoa as an intercrop resulted in higher ASI both in basins and interspace due to improved SOM with litterfall of cocoa. Supporting this, several authors (Briedis et al., 2012; Carmeis Filho et al., 2016; Martins et al., 2013) reported that the formation of large aggregates with greater stability in soils with higher organic matter. ASI showed a positive relationship with GMD and GRSP (Figure 4a and 4c). In addition, roots are thought to be the primary source of labile organic matter, and the mucilage secreted by them is essential for the stability of the aggregates (Traoré

et al., 2000). Planting cocoa as an intercrop in OP plantations enhanced aggregate stability, which in turn improves soil structure and protects the soil from erosion.

Soil aggregation and its stability are also influenced by GRSP present in the soil. Glomalin protein increases the aggregation formation and its stability (Jia et al., 2025; Masebo et al., 2025). It is made up of carbohydrates, proteins, aliphatic components, and multivalent cations. Research (Cai et al., 2023; Ling et al., 2025; Wang et al., 2021) found that this microbial product functions as a glue to hold soil particles together by creating bridges between SOM and clay through multivalent cations or other elements and causes aggregation. In this study, we observed a significant effect of cropping system, sampling point and soil depth on GRSP (Figure 3c). This protein decreased with depth irrespective of the cropping system and sampling point. A decrease in SOM might be the possible cause for such reduction (Xie et al., 2015). The flocculating property of GRSP is responsible

for the formation of macroaggregates (Wang et al., 2021). Our results showed that inclusion of cocoa as an intercrop in the oil palm-based cropping system improved the GRSP concentration in the soil by 11.8%–54.6%. Addition of organic matter through OP and cocoa crops significantly increases GRSP by improving soil conditions and

providing carbon sources to soil microorganisms, specifically arbuscular mycorrhizal fungi, which produce this protein (Singh et al., 2018). Supporting this, a positive relationship was noticed between TOC content and GRSP. A positive correlation was also observed between GRSP and ASI (Figure 4d and 4e).

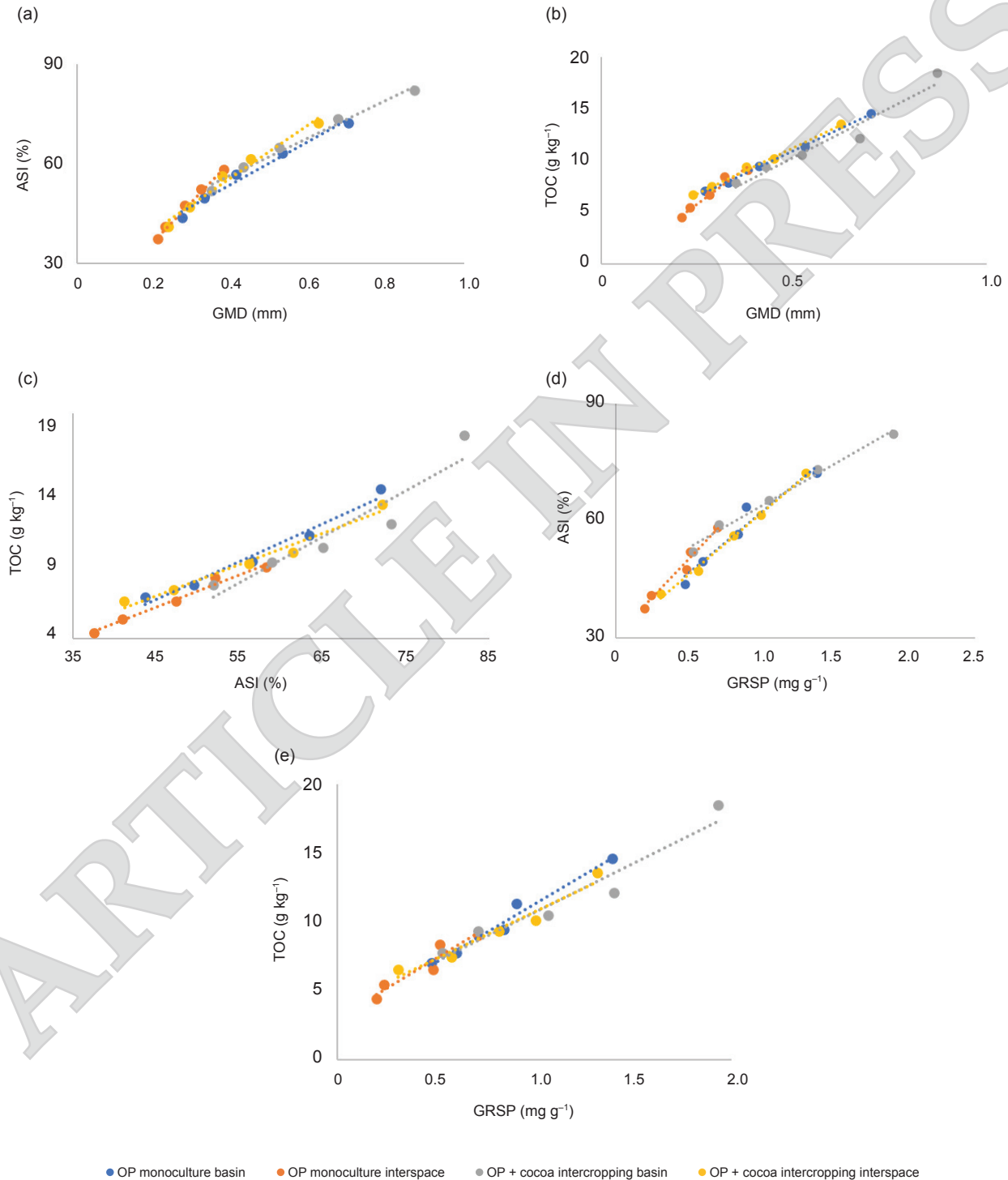


Figure 4. Relationship between (a) geometric mean diameter (GMD) and aggregate stability index (ASI), (b) GMD and total organic carbon (TOC), (c) ASI and TOC, (d) glomalin-related soil protein (GRSP) and ASI, (e) GRSP and TOC.

The TOC and TN ranged from 4.42 to 18.43 and 0.62 to 1.47 g kg⁻¹ at soil depths of 0 to 100 cm (Table 2). We found that the interplay of cropping system, sample location and depth had a substantial effect on TOC and TN. Irrespective of cropping system and sampling point, TOC and TN decreased with soil depth. The majority of organic inputs originate at or close to the soil's surface as oil palm-based farming practices adopt undisturbed soil conditions, which could be the reason why TOC decreased with soil depth. OP + cocoa intercropping outperformed OP monoculture in terms of TOC and TN by 6.8%–49.7% and 3.0%–28.1%, respectively. When comparing the sampling locations, the basin showed the highest TOC and TN compared to the interspace. Basins of OP + cocoa intercropping recorded the highest TOC, and the lowest was noticed in the interspace of OP monoculture. Mature OP farms produce 15–17 t ha⁻¹ of biomass; mulching palm circles with such wastes increased soil C (Manorama et al., 2021). According to an earlier investigation (Agbotui et al., 2024) on C and nutrient cycling under cocoa-based agroforestry systems, regular litterfall from cocoa was associated with a steady supply of SOM, which enhanced the TOC and TN concentration. The crop residues contain nitrogen and other nutrients; adding such residues to soil enhances the soil by mineralisation (Lou et al., 2023; Tang et al., 2024). Considering the relationship between TOC and aggregate stability, TOC showed a positive association with GMD, GRSP and ASI (Figure 4b, 4c and 4e).

Soil aggregates store and cycle TOC and TN, which are necessary for terrestrial ecosystems to operate. The TOC and TN distribution in aggregates

of varied sizes was significantly affected by cropping system, sampling point and soil depth (Figure 5 and 6). TOC ranged from 2.26 to 17.5, 6.76 to 21.0, 8.34 to 24.2 and 6.02 to 21.4 g kg⁻¹ in silt + clay fraction, microaggregates, small macroaggregates and large microaggregates, respectively. Similarly, TN ranged from 0.69 to 1.55, 0.70 to 1.84, 0.74 to 1.89 and 0.80 to 2.02 g kg⁻¹, respectively, in silt + clay fraction, microaggregates, small macroaggregates and large microaggregates. TOC and TN in aggregates decreased significantly across soil depth, regardless of cropping system and sampling location. A similar trend was also reported by Gelaw et al. (2013). Higher organic inputs at or near the soil surface and minimal soil disturbance practised in OP based cropping systems may be the possible cause for such a decline (Ji et al., 2019; Song et al., 2019). Intercropping cocoa in OP plantations enhanced the TOC present in silt + clay, microaggregates, small macroaggregates and large macroaggregates by 9.56%–76.20%, 3.27%–25.60%, 6.91%–34.20% and 7.86%–30.0%, respectively, compared to OP monoculture.

Similarly, OP monoculture recorded 6.61%–25.70%, 10.90%–22.80%, 11.80%–30.80% and 2.21%–30.00% lower TN in silt + clay, microaggregates, small macroaggregates and large macroaggregates, respectively. Results showed that the soil macroaggregates (>0.25 mm) contain higher concentrations of TOC and TN in most soil depths compared to microaggregates (<0.25 mm). This is because macroaggregates are formed by binding microaggregates together with fresh organic matter, fungal hyphae and roots, making them richer in C and nutrients (Shan & Yan, 2013). Aggregates with higher stability provide

TABLE 2. EFFECT OF DIFFERENT OIL PALM-BASED CROPPING SYSTEM ON TOTAL ORGANIC CARBON (TOC) AND TOTAL NITROGEN (TN) CONTENT OF THE SOILS

Soil depth	OP monoculture		OP + cocoa intercropping	
	OP basin	Interspace	OP basin	Interspace
TOC (g kg ⁻¹)				
0–20 cm	14.57 ^b	9.03 ⁱ	18.43 ^a	13.52 ^c
20–40 cm	11.33 ^e	8.30 ^j	12.10 ^d	10.13 ^g
40–60 cm	9.46 ^h	6.57 ⁿ	10.47 ^f	9.30 ^{hi}
60–80 cm	7.80 ^k	5.37 ^o	9.33 ^h	7.42 ^l
80–100 cm	6.97 ^m	4.42 ^p	7.80 ^k	6.56 ⁿ
TN (g kg ⁻¹)				
0–20 cm	1.26 ^b	0.96 ^f	1.47 ^a	1.23 ^c
20–40 cm	1.00 ^e	0.90 ^g	1.03 ^d	0.94 ^f
40–60 cm	0.90 ^g	0.75 ^j	0.98 ^e	0.89 ^g
60–80 cm	0.81 ⁱ	0.68 ^l	0.94 ^f	0.79 ⁱ
80–100 cm	0.76 ^j	0.62 ^m	0.83 ^h	0.72 ^k

Note: Various lowercase letters indicate significant differences among different cropping systems, sampling locations, and soil depths at $p < 0.05$; OP – oil palm.

maximum protection of TOC and TN contained within them (Sekaran et al., 2021). Somasundaram et al. (2018) found higher SOC in aggregates of large size (macroaggregates) compared to microaggregates. Basins of OP plantations showed higher aggregate-associated TOC (5.33%–88.0%) and TN (5.64%–45.2%) compared to the interspace. The root biomass of the OP promotes microbial activity that enhances the TOC (Zhang et al., 2012). Regardless of sampling location, OP + cocoa intercropping showed higher TOC and TN content in all aggregate fractions due to *in situ* addition of higher quantities of organic residues. Basins of OP + cocoa intercropping showed higher TOC and TN, whereas the interspace of the OP monoculture system showed the minimum values in most of the soil depths. The addition of biomass and the biotic impact of palms may have stimulated soil microbial activities and enhanced organic matter cycling in OP based cropping system of the tropical region. TOC and TN contained in aggregates of different sizes showed a positive relationship with GMD of aggregates, ASI, GRSP and a negative relationship with soil bulk density (Table 3).

The CPC was computed to analyse the ability of soil aggregates to store carbon. CPC ranged from 1.10 to 5.05, 1.53 to 4.05, 3.27 to 16.60 and 0.80 to 7.31 g kg⁻¹, respectively, in silt + clay fraction,

microaggregates, small macroaggregates and large macroaggregates. Basins of OP plantations with cocoa intercropping recorded higher CPC, whereas the lowest was found in the interspace of OP monoculture in all aggregate fractions except the silt + clay fraction (Figure 7). Our findings indicated that intercropping cocoa in OP plantations enhanced the soil aggregate's ability to store carbon. It improved the CPC of microaggregates, small macroaggregates and large macroaggregates by 1.88%–35.90%, 5.49%–40.00% and 13.90%–71.00%, respectively. Leaving OP biomass (pruned fronds, dried male inflorescence, etc.) on the surface and adoption of cocoa intercropping added high amounts of organic material to the soil, boosting the formation of stable soil aggregates. These stable macroaggregates trap and protect carbon, significantly increasing its residence time in the soil (Totsche et al., 2018). Small macroaggregate fractions had the highest C storage capacity among the aggregate fractions. The small macroaggregates' significant carbon reserve showed their importance in C sequestration in the OP based cropping system.

Considering the CPC of the silt + clay fraction, basins of the plantations with cocoa intercropping showed lower values compared to their interspace sampling and OP monoculture in topsoil layers. Diverse residue inputs in the cocoa

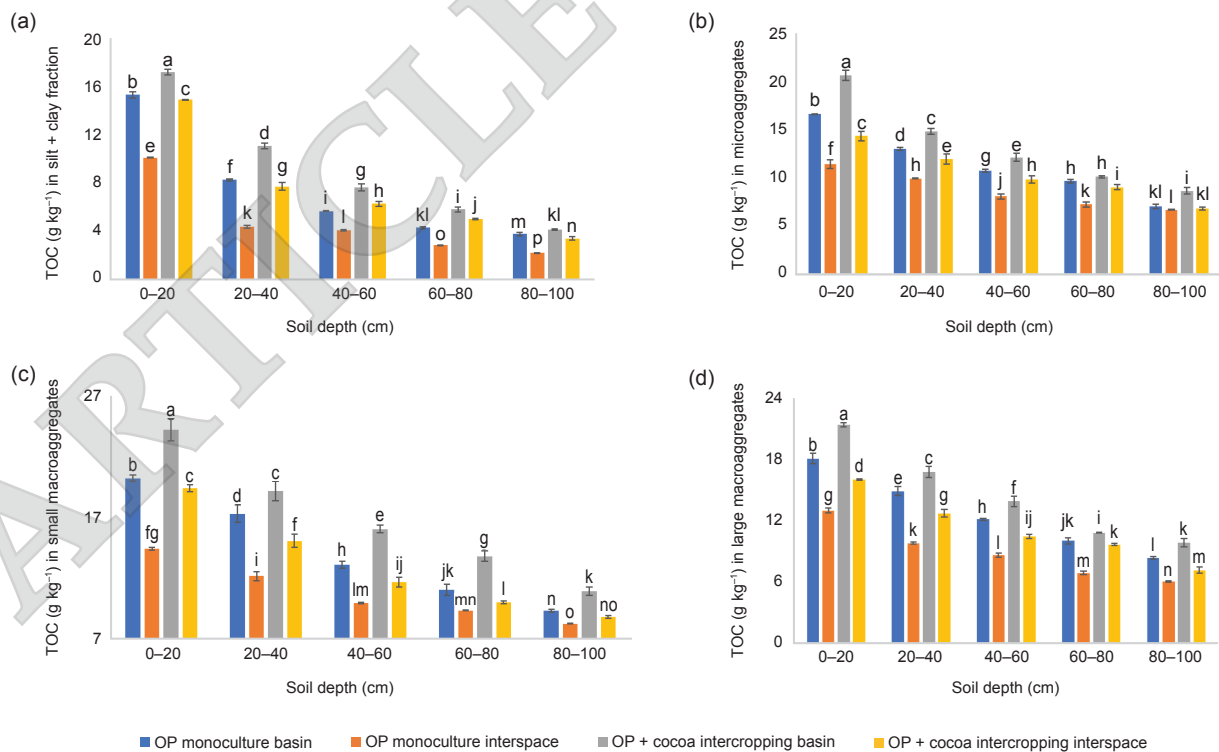


Figure 5. Effect of different oil palm (OP) based cropping systems on aggregate-associated total organic carbon (TOC) in (a) silt + clay fraction; (b) microaggregates; (c) small macroaggregates; and (d) large macroaggregates. Various lowercase letters indicate significant differences among different cropping systems, sampling locations, and soil depths at $p < 0.05$.

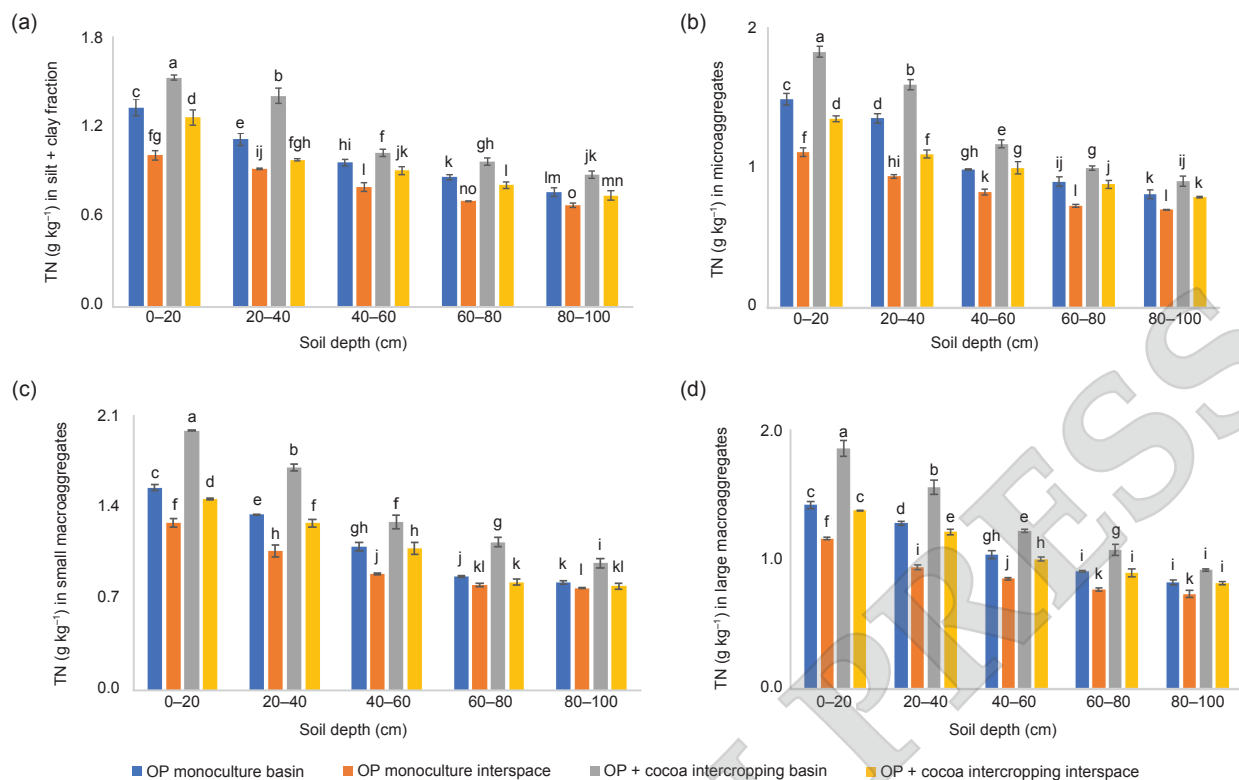


Figure 6. Effect of different oil palm (OP) based cropping systems on aggregate-associated total nitrogen (TN) in (a) silt + clay fraction; (b) microaggregates; (c) small macroaggregates; and (d) large macroaggregates. Various lowercase letters indicate significant differences among different cropping systems, sampling locations, and soil depths at $p < 0.05$.

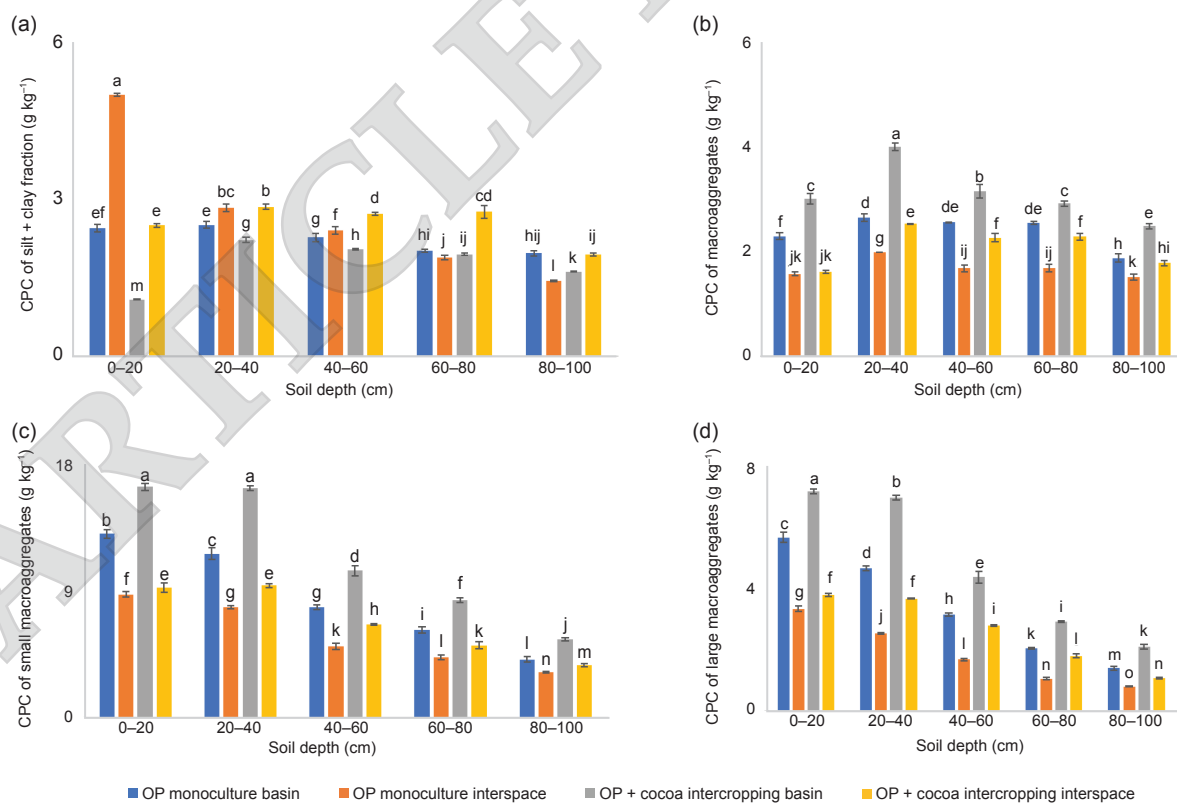


Figure 7. Effect of different oil palm (OP) based cropping systems on carbon preservation capacity (CPC) of (a) silt + clay fraction; (b) microaggregates; (c) small macroaggregates; and (d) large macroaggregates. Various lowercase letters indicate significant differences among different cropping systems, sampling locations and soil depths at $p < 0.05$.

TABLE 3. CORRELATION OF SOIL PROPERTIES IN SOILS OF OIL PALM (OP) BASED CROPPING SYSTEM

Item	TOC (mm)				TN (mm)				CPC (mm)			
	<0.053	0.053-0.25	0.25-2.0	>2.0	<0.053	0.053-0.25	0.25-2.0	>2.0	<0.053	0.053-0.25	0.25-2.0	>2.0
BD	-0.943**	-0.923**	-0.938**	-0.938**	-0.916**	-0.910**	-0.920**	-0.912**	-0.212	-0.418**	-0.856**	-0.868**
GMD	0.935**	0.978**	0.983**	0.980**	0.975**	0.978**	0.977**	0.970**	-0.107	0.594**	0.943**	0.958**
ASI	0.922**	0.960**	0.977**	0.978**	0.965**	0.959**	0.960**	0.956**	0.044	0.593**	0.941**	0.951**
GRSP	0.942**	0.978**	0.969**	0.974**	0.962**	0.962**	0.974**	0.972**	0.020	0.540**	0.933**	0.948**
TOC	0.947**	0.976**	0.968**	0.973**	0.953**	0.957**	0.960**	0.947**	-0.052	0.501**	0.898**	0.916**
TN	0.959**	0.964**	0.960**	0.959**	0.937**	0.930**	0.937**	0.932**	0.008	0.415**	0.864**	0.879**

Note: * $P < 0.05$; ** $P < 0.01$; BD - bulk density; GMD - geometric mean diameter; ASI - aggregate stability index; TOC - total organic carbon; TN - total nitrogen; CPC - carbon preservation capacity; TOC <0.053 mm - TOC in silt + clay fraction; TOC 0.053-0.25 mm - TOC in microaggregates; TOC 0.25-2.00 mm - TOC in small macroaggregates; TOC >2.0 mm - TOC in large macroaggregates; TN <0.053 mm - TN in silt + clay fraction; TN 0.053-0.25 mm - TN in microaggregates; TN 0.25-2.0 mm - TN in small macroaggregates; TN >2.0 mm - TN in large macroaggregates; CPC <0.053 mm - CPC of silt + clay fraction; CPC 0.053-0.25 mm - CPC of microaggregates; CPC 0.25-2.00 mm - CPC of small macroaggregates; CPC >2.0 mm - CPC of large macroaggregates.

intercropped system might have increased the labile C pool in the silt + clay fraction. This labile C is less protected and more accessible to microbes than the carbon tucked away inside aggregates (Peng et al., 2024), thus reducing its long-term preservation capacity. Supporting this, higher microbial biomass carbon (labile C) in intercropping than sole crop was reported by Zhao et al. (2023).

Large macroaggregates store carbon quickly and release it just as quickly upon disturbance, as they are rich in particulate organic carbon, which is the most active, labile (easily decomposed) fraction of organic matter (Ye et al., 2020; Zhang et al., 2022). Similarly, Sekaran et al. (2021) reported maximum CPC in small macroaggregates compared to microaggregates. CPC of different aggregate fractions showed a negative relationship with bulk density, and a significant positive relationship with GMD of aggregates, ASI and GRSP. High bulk density is associated with poor soil structure and less organic matter, which results in more unstable aggregates and lower carbon preservation (Majamo et al., 2025). More GRSP means more stable and larger aggregates (higher GMD & ASI) with better carbon preservation. Our results highlight the likely benefits associated with cocoa intercropping in OP plantations for preserving high soil carbon, which remains protected from microbial degradation by soil aggregation.

CONCLUSION

In the present investigation, intercropping of cocoa in OP plantations outperformed OP monoculture in terms of improving the GMD of the aggregates, ASI, TOC, TN and GRSP. Introduction of cocoa in OP improved the stability of the aggregates, which in turn improves the soil structure and protects the soil from erosion. Intercropping improved the estimated soil properties both in the interspace and basin area. Furthermore, under cocoa intercropping in OP plantations, the TOC and TN contained in different aggregate fractions also improved. The result suggested that intercropping increased the C preservation capacity of the soil aggregates, particularly micro and macroaggregates, by 1.88%–71.00%. Small macroaggregate fractions were the aggregate fractions with the greatest capacity to store carbon compared to aggregates <0.25 mm. Relationship analysis suggested that TOC and GRSP play a vital role in the stability of soil aggregates. The study emphasises the positive impact of crop residue addition under cocoa intercropping for improving the soil properties. Though mulching of OP basins with crop residues improved the soil properties, introduction of cocoa aids in further enhancing the soils of both basins and interspace.

Overall, the study emphasises the positive impact of crop residue addition under cocoa intercropping for improving the soil properties and soil health. This study suggests that cocoa intercropping in OP plantations provides a viable strategy to enhance long-term sustainability, offering higher land equivalent ratios, income diversification, and the mitigation of the ecological footprint of monoculture systems. Further advanced research employing soil metagenomics is crucial to uncover the long-term impact of oil palm-based cropping systems on functional microbial communities.

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