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Soil Organic Carbon Stock and Potential Forage in Smallholder Oil Palm Plantations in Muaro Jambi Regency, Indonesia

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Abstract **Original Research Article**

Soil organic carbon (SOC), a vital component of soil organic matter (SOM), is derived from vegetation residues and soil organisms and plays a significant role in climate change and sustainable development. This study focused on estimating SOC stock (0-60 cm depth) and assessing the potential of understorey plants as forage in smallholder oil palm plantations in Suka Maju Village, Muaro Jambi Regency. A survey across 916.5 hectares revealed that SOC stock ranged from 91.48 to 150.50 tons per hectare, exceeding 100 tons on land with plants older than 10 years. The highest SOC stock was found on 20-year-old plants on 8% sloped land. Among 19 understorey species identified, four showed promise as green fodder, with *Asystasia gangetica* being the most widespread, dominating areas with older plants.
Keywords: forage, oil palm, smallholder plantation, SOC stock, understory.

1. INTRODUCTION

Soil organic carbon (SOC) is a crucial component of the broader global carbon cycle, which encompasses the movement of carbon through soil, vegetation, oceans, and the atmosphere. SOC is a key part of soil organic matter (SOM) (Clara *et al.*, 2017; Bot and Benites, 2005) and serves as an important indicator of soil fertility, sustainability (Wolf and Sneyder, 2003), and overall soil quality (Islam and Well, 2000). As soil fertility increases, so does SOC (Hairiah *et al.*, 2011). Soil acts as a significant carbon reservoir, holding more carbon than both the atmosphere and terrestrial vegetation combined. It is estimated that the global SOC stock is nearly three times the amount of carbon found in biomass and twice that found in the atmosphere (Eswaran *et al.*, 1993). On average, there are about 1,500 petagrams (Pg) of carbon in the top meter of soil, although this distribution can vary over time and across different locations. The release of SOC into the atmosphere contributes to climate change and global warming. Consequently, SOC is not only important for food production, but it also plays a vital role in mitigating and adapting to climate change, and in achieving sustainable development goals (Clara *et al.*, 2017).

Soil organic carbon originates from vegetation residues, such as litter, crop residues, and dead roots, as well as from soil organisms (Hairiah *et al.*, 2011). Once carbon enters the soil in the form of organic matter from soil flora and fauna, it can persist for decades, centuries, or even millennia. However, SOC is dynamic, and human activities can either transform it into a net sink or a net source of greenhouse gases. Research shows that SOC stock in oil palm plantations with cover crops ranges from 35.9 to 37.7 tons per hectare, compared to only 21.2 tons per hectare in plantations without cover crops (Alfarizi *et al.*, 2023). Conventional farming practices, such as monoculture systems, may decrease SOC stock and increase emissions due to the faster decomposition of soil organic matter in exposed soil (Yustika *et al.*, 2014). Therefore, the amount of SOC stock is influenced by factors such as plant and crop diversity, plant density, soil type, and soil management practices (Hairiah *et al.*, 2011).

Soil has become one of the world's most vulnerable resources in the face of climate change, land degradation, and biodiversity loss. Drylands, which are typically characterised by low soil organic carbon (SOC) content, are particularly concerning, as are peatlands. However, with careful management, drylands have the potential to absorb significant amounts of carbon in their soils, contributing to climate change mitigation and adaptation (Clara *et al.*, 2017). In Indonesia, drylands are primarily composed of Inceptisols, covering an area of approximately 70,520,000 hectares, of which 1,620,000 hectares are located in Jambi Province. Much of this land has been designated for plantations, particularly for oil palm and rubber cultivation. The soil organic matter (SOM) content of Inceptisols in various regions of Indonesia ranges from low to moderate in some areas, while others exhibit moderate to high levels. Consequently, the natural fertility potential of Inceptisols generally varies from low to high (Hidayat and Mulyani, 2002).

Oil palm is a key tropical crop for global oil, providing significant financial benefits. However, its expansion threatens the environment by reducing biodiversity (Meijaard *et al*., 2018) and contributing to climate change. Increased palm oil production is linked to higher greenhouse gas emissions in Indonesia's agricultural sector. The palm oil industry has the potential to help combat global warming by reabsorbing carbon emissions through photosynthesis. Oil palm plantations can also support reforestation by turning low-carbon land into high-carbon land. With their intensive root systems and high production yield, oil palms act as effective “biological machines” for absorbing CO_2 (PAPSI, 2021). Research in North Sumatra shows that oil palm plantations managed under best practices have soil organic carbon (SOC) stocks of 68 tons per hectare, which is significantly higher than the 57 tons and 46 tons per hectare found in current management and smallholder practices, respectively (Rahman *et al*., 2021).

Oil palm plantations are found across 26 provinces in Indonesia, primarily on the islands of Sumatra and Kalimantan. The majority of these plantations are privately owned, accounting for 55.74% of the total area, while smallholder plantations make up 40.38%, and state-owned plantations represent the remaining 3.56%. In 2022, the total area of oil palm plantations reached 15,388,556 hectares, which includes 548,311 hectares of government plantations, 8,576,838 hectares of private plantations, and 6,213,407 hectares of smallholder plantations (Directorate of Statistics of Food Crops, Horticulture, and Plantations, 2023). By 2024, the area of smallholder oil palm plantations is projected to increase to 6,783,100 hectares, representing 42.38% of the total 16,005,060 hectares of oil palm plantations in Indonesia (BPS, 2024). This trend reflects a growing interest in oil palm cultivation, primarily driven by the high financial returns compared to other plantation crops. In Jambi Province, oil palm plantations covered 952,150 hectares in 2023, with smallholder plantations comprising the majority at 67.82% (645,706 hectares). Private plantations accounted for 29.18% (277,796 hectares), and state plantations made up 3.01% (228,648 hectares) (Directorate of Food Crops, Horticulture, and Estate Crops Statistics, 2024). Although smallholder oil palm plantations are typically smaller than large corporate plantations, they are essential to national palm oil production. However, the use of technology and fertilizers in these smallholder operations often lags behind that of larger companies. A lack of knowledge and access to the latest technologies such as superior seed varieties, modern cultivation techniques, and effective post-harvest management poses significant challenges, resulting in lower operational efficiency and production quality (PASPI, 2025).

SOC stocks in oil palm plantations also include understorey plants that are often considered or treated as weeds. However, *Nephrolepis biserrata* can produce biomass ranging from 21.2 to 27.1 tons per hectare, with a decomposition period of 30 to 60 days, plant carbon content of 0.9 tons of carbon per hectare per year, and a soil organic carbon (SOC) stock of 14.7 to 15.7 tons per hectare per year. Meanwhile, *Asystasia intrusa* produces biomass weighing between 17.6 and 17.9 tons per hectare, with a similar decomposition period of 30 to 60 days, plant carbon content of 0.9 tons of carbon per hectare per year, and a soil carbon stock of 13.2 to 13.9 tons per hectare per year (Satriawan *et al*., 2022). These understorey plants also have the potential to serve as a source of green fodder. Most grass and legume types that grow under oil palm stands are preferred by livestock. However, many weeds found in these areas are not favoured by animals. Among the various plants growing under oil palm stands, weeds are the most common type. In addition to grass and legumes, other plant species preferred by livestock include *Asystasia intrusa* and *Borreria latifolia*. While Sida sp. is only favoured for its shoots, plants like *Melastoma* sp. are generally disliked by livestock (Herdiawan *et al*., 2022). This study aims to identify the potential of understorey plants for forage and estimate soil carbon storage in smallholder oil palm plantations in the Mestong District of Muara Jambi Regency.

2. METHODOLOGY

The study utilised a semi-detailed survey method, employing a working map at a scale of 1:50,000 based on a homogeneous land unit (HLU) map of Suka Maju Village. This was created using ArcGIS 10.5 software, which overlaid land use maps, slope maps, and soil type maps specific to the village. Suka Maju Village covers an area of 4,469.67 hectares in Mestong District, Muaro Jambi Regency, Jambi Province. It is located approximately 12 km from Sengeti, the district capital, and 20 km from Jambi City, the provincial capital. Geographically, Suka Maju Village is positioned at coordinates 103º35’33’’-103º38’52’’E and 1º41’55’’-1º49’35’’S, at an elevation of 56 meters above sea level. According to the Schmidt and Ferguson Climate Classification (1980), the climate of this village is classified as Type A (very wet), with a Q value of 0.086 and an average annual rainfall of 2,555.2 mm (or approximately 212.93 mm per month). The average air temperature in Suka Maju Village ranges from 26.4 to 27.4 °C, with an average humidity of 85.2%.

The land in Suka Maju Village is predominantly classified as Typic Dystrudepts (Entisol with a Udic moisture regime). This classification is based on soil type maps derived from the Semi-Detailed Land Map at a scale of 1:50,000 for Muaro Jambi Regency (BPPP, 2016). Land use maps were created using Sentinel-2 Satellite Imagery from 2021, and slope gradient maps were developed from SRTM DEM data provided by the Geospatial Information Agency. The HLU (Higher Land Use) map indicates that the land designated for smallholder oil palm plantations in Suka Maju Village encompasses 11 HLUs over an area of 935.3 hectares. Observation points and soil sampling (OPSs) were strategically placed on the HLU map using a purposive stratified random sampling method. The number of OPSs was proportionate to the area of each HLU, resulting in a working map containing 16 OPSs (Table 1)

Table 1: Homogeneous land unit (HLU) and distribution of observation points and soil sampling (OS) in smallholder oil palm plantations in Suka Maju Village, Muaro Jambi Regency, Indonesia

HLU	Slope (%)		Age of oil palm (year)	Wide (ha)	Number of OPSs
	class	dominant			
HLU-45	0-3	2, 3	9, 11	302.3	2
HLU-46	3-8	4, 6, 7, 8	70,10, 20	440.2	4
HLU-47	8-15	9	7	107.3	1
HLU-49	0-3	2	10	16.8	1
HLU-50	3-8	4	10	38.7	1
HLU-51	8-15	8	15	11.2	1
Total				916.5	10

Preliminary survey results and ground checks of the working map revealed that three hlus are characterised as swampy land (flooded). Additionally, one HLU (HLU-45) is not a smallholder plantation but belongs to a private palm oil plantation. HLUs with slopes ranging from 15 to 30% are relatively small in area and were not observed in the field. Supporting data from BBSDLP (2016) indicates that 71.31% of Muaro Jambi Regency is flat to somewhat flat (slope of 0-3 percent), while 11.78% is wavy (slope of 3-8 percent), 13.03% is moderately wavy (slope of 8-15 percent), and 2.89% is hilly (slope of 15-30 percent across 2 hlus). Consequently, the survey was conducted across 6 hlus with 10 OPSs, with each ops being situated in areas that exhibit dominant slopes and varying plant ages (as detailed in table 1). Soil sampling and observations at each ops were carried out with three replications.

The stock of soil SOC in each operational payment system (ops) across different land use classifications (HLU) was estimated by multiplying the soil organic carbon percentage by the soil bulk density (kg/m^3) and the soil depth (m). SOC content was determined using the Walkley And Black Method. Bulk density is calculated as the weight of oven-dried soil (105 °c, for 48 hours) divided by the volume of the soil sample taken in a ring. Soil depth was categorised into three ranges: 0-10 cm, 10-30 cm, and 30-60 cm. Additionally, the soil organic matter (som) content was calculated using the formula som = soc × 1.724. The soil ph was measured using a ph meter with a glass electrode, which serves as an indicator of potential soil fertility. The data were statistically analysed using the F-test, followed by the Duncan Multiple Range Test at a 5% confidence level.

3. RESULT AND DISCUSSION

Plant Condition and Soil Coverage

Smallholder oil palm plantations in Suka Maju Village have not adopted Good Agricultural Practices (GAP) (Bronkhorst *et al*., 2017), leading to inadequate plant fertility and suboptimal soil cover (see Figure 1). Farmers do not use leguminous cover crops (LCC) in the early stages and fail to apply fertiliser according to soil characteristics and plant needs regarding type, dosage, timing, and method. Additionally, plant maintenance is often neglected. Planting LCC is essential in oil palm plantations, particularly for maintaining soil moisture and preventing soil damage from raindrop impact, surface runoff, and erosion, especially on sloping land. Furthermore, LCC improves soil fertility through the decomposition of organic matter and provides nitrogen, which is beneficial for plant growth (Nora and Mual, 2018).

The use of chemical fertilisers in oil palm cultivation involves creating a 1.5-meter strip around each plant, kept free of weeds and covered with dead fronds to enhance nutrient absorption. Typically, NPK fertilisers are spread on the soil surface between 0.5 and 1 meter from the main stem. Standard practices recommend planting 135 to 145 oil palms per hectare, with spacing of 8.6 m x 8.6 m to 8.2 m x 8.2 m in a triangular or pentagonal pattern (Nora and Mual, 2018). Farmers often vary the spacing from 9.4 m x 9.4 m to 8.1 m x 8.2 m, resulting in densities of 114 to 151 palms per hectare. Proper spacing is crucial, as too close a planting can limit sunlight access, while too wide can lead to low yields without adequate fertilisation and maintenance.

Farmers' oil palms, aged 7 to 20 years, are often poorly maintained, leading to issues with weed infestations, particularly the fern *Nephrolepis biserrata* at sites like SLH-45 and SLH-50. These ferns disrupt fruit production and harvest times, while loose fronds embedded in the trunk can cause yield loss and worsen weed growth. Weeds compete for nutrients and light, disturb the microclimate, and clog drainage channels, resulting in waterlogging and reduced productivity (Ministry of Agriculture, 2021). The prevalence of weed species varies by location, influenced by environmental factors. Thus, implementing effective plantation management practices such as proper maintenance, fertilisation, pest control, and efficient harvesting is crucial for minimising losses and enhancing yields (Rahman *et al*., 2021).

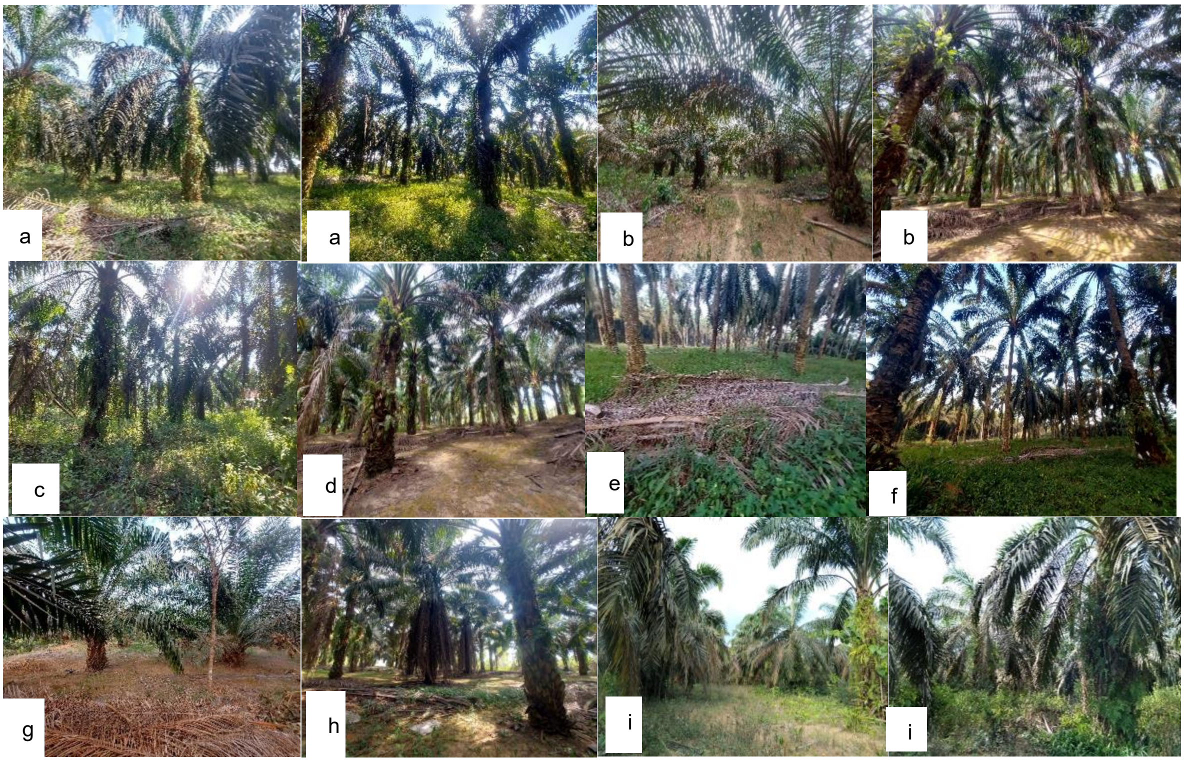

Figure 1 - Plant conditions and soil surface cover at SLH-45 (a-b), SLH-46 (c-f), SLH-47 (g), SLH-49 (h), SLH-50 (i), and SLH-51(j) smallholders' oil palm plantations in Suka Maju Village, Muara Jambi Regency

Understorey Plants and Potential Forage

The understorey plants in smallholder oil palm plantations in Suka Maju Village include 27 species, of which eight are potential forage plants. The dominant weed species varied across different management units (HLUs), with their distribution ranging from 30% to 76%. Miconia crenata was identified as the weed species present in all HLUs, except for HLU-50 and HLU-51. Meanwhile, *Croton hirtus* L. was only found in HLU-46, which has a 4% slope and contains 7-year-old plants (see Table 2). *Miconia crenata* is a shrub from the *Melastomataceae* family, native to humid tropical biomes (IPNI, 2024). This woody herb can thrive in shaded areas beneath trees and tends to become very dense in open spaces, thereby inhibiting the growth of other species (Sitepu, 2020).

Understorey potential for animal feed includes eight species of weeds and grasses. Suitable grass species are *Axonopus compressus, Centotheca philippinensis, Leersia* sp., *Paspalum plicatulum,* and *Paspalum conjugatum.* The weeds *Asystasia gangetica* and *Oxalis barrelieri* L. are also included, with a distribution of 35-84%. Forage is primarily located in SLH-46, with 11-year-old plants on a 4% slope, and in SLH-51. Key forage species for cattle and goats are *A. gangetica, A. compressus,* and *P. conjugatum.*

A. gangetica and A. compressus are the two forage species found in all High-Land Units (HLUs), except for HLU-46a and HLU-50, with a distribution range of 35-84%. *Oxalis barrelieri* L. is a potential legume forage species that occurs only in HLU-46 (see Table 2). *A. gangetica* is a broadleaf weed commonly found in oil palm plantations on dry land, while *A. compressus* is a mild weed that can be tolerated (Ditjenbun, 2021). *A. gangetica* can reproduce vegetatively through cuttings and generatively through seeds. Its branched taproot system allows each stem node to produce roots upon soil contact. This species is suitable as ground cover in oil palm plantations, as it is easy to propagate, contributes nutrients like nitrogen (N), phosphorus (P), and potassium (K), and improves soil by recycling nutrients. *A. gangetica* is the dominant understorey plant found under oil palm stands that are 9, 13, and 18 years old, exhibiting a higher relative frequency and relative dominance value compared to other vegetation. It has the most individuals, is always present, and has a wide distribution (Asbur *et al*., 2018). However, the biomass loss of *A. gangetica* in the field occurs much more rapidly than the weight loss of oil palm fronds and other weeds, such as *Melastoma malabathricum* L. (Yahya *et al*., 2022). *M. malabathricum* takes approximately 14 months to decompose, with biomass weight losses of 87.6%. Planting land with A. gangetica can increase SOC stock by 100% at every depth of the soil profile. The increase in SOC stock following the planting of *A. gangetica* is attributed to the rise in soil organic carbon levels, which can reach 39.5 tons per hectare (Asbur *et al*., 2015).

Table 2: Types of understorey vegetation (weeds and potential forage) and their distribution under smallholder oil palm plantations in Suka Maju Village

HLU	Slope (%)	Age of oil palm (years)	Understorey Plant Type			
			Weed	Distribu-tion (%)	Green fodder	Distribu-tion (%)
HLU-45	3	11	*Ageratum conyzoides, Boreria alata, Miconia crenata, Rolandra fruticosa* (L.) Kuntze, *Phyllanthus urinaria, Vandellia diffusa* L.	35	*Asystasia ganggetica Axonopus compressus Centotheca philippinensis, Leersia* sp	65
HLU-45	2	9	*Boreria alata, Miconia crenata Phyllanthus urinaria, Praxelis clematidea*	50	*A. ganggetica Axonopus compressus Paspalum plicatulum*	50
HLU-46	4	7	*Croton hircus* L., *Melastoma malabathricum* L., *M. crenata, P. urinaria*, *Spermacoce latifolia, Vandellia diffusa* L., *Lycopodiella cernua* (L.) Pic.Serm., *Lygodium palmatum* (Bernh.) Sw., *Phegopteris connectilis*	71	*Leersia* sp *Oxalis barrelieri L.*	29
HLU-46	6	10	*Miconia crenata, Phyllanthus urinaria Nephrolepis exallata, Scleria*	16	*A. ganggetica A. compressus Ottochloa nodosa C. philippinensis*	84
Hlu-46	7	20	*Melastoma malabatricum, Miconia crenata, Peperomia pellucida P. urinaria, Praxelis clematidea Spermacoce exilis* (L.O.Williams) C.D.Adams ex W.C.Burger & C.M.Taylor, *V. diffusa* L, *Scleria*	30	*Asystasia ganggetica Axonopus compressus Centotheca philippinensis Leersia* sp	70
HLU-46	8	20	*M. malabatricum, M. crenata Peperomia pellucida, P. urinaria P. clematidea, S. exilis* (L.O.Williams) C.D.Adams ex W.C.Burger & C.M.Taylor, *V. diffusa* L, *Scleria*	30	*Asystasia ganggetica Axonopus compressus Centotheca philippinensis Leersia* sp	70
HLU-47	9	7	*Melastoma malabatricum, M.crenata Microlepia speluncae* (L.) T. Moore *Pyrrosia lingua* (Thunb.) Farw.	45	*Asystasia ganggetica Ottochloa nodosa C.philippinensis*	55
HLU-48	3	10	*Ageratum conyzoides, Boreria alata Miconia crenata, Rolandra fruticosa* (L.) Kuntze, *P. urinaria Vandellia diffusa* L.	35	*A. ganggetica A. compressus C. philippinensis Leersia* sp	65
HLU-50	8	10	*Boreria., Mimosa invisa, R. fruticosa* (L.) Kuntze, *Sida linifolia* Juss. ex Cav., *Vandellia diffusa* L, *Dicranopteris linearis* syn. *G. linearis*	50	*Ottochloa nodosa Centotheca philippinensis*	50
HLU-51	10	15	*A. conyzoides, B. alata S. nodiflora* (L.) Gaertn., *P. urinaria, P.clematidea, S. Exilis*(L.O.Williams), C.D.Adams ex W.C.Burger & C.M.Taylor, V. *diffusa* L.	65	*Asystasia ganggetica Axonopus compressus Paspalum conjugatum*	35

M. malabathricum L. is a plant species that thrives in well-drained, fertile soils and is considered a significant weed in pastures, pineapple crops, and oil palm plantations. Native to Indonesia, it often grows as a pioneer plant in open areas and is recognised as a noxious and invasive weed due to its rapid growth and prolific seed production (Setyawati *et al*., 2015; Madusari, 2016).

Soil Organic Carbon, Bulk Density, Organic Matter, and pH

Soil organic carbon (SOC) levels in the smallholder oil palm plantation of Suka Maju Village, characterised by a slope of 7-10 % and plant ages ranging from 7 to 20 years, vary significantly. In the upper layer (0-10 cm), SOC levels range from low (1.62%) to high (3.62%). In the 10-30 cm layer, SOC decreases to between 1.17% and 2.36%, and further declines in the 30-60 cm layer, where it ranges from 0.58% to 1.55%. Notably, SOC is classified as high only in the upper layer of plantation SLH-46, which has slopes of 7% and 8% and comprises 20-year-old plants, the oldest in the study. This SOC level is significantly higher compared to SLH-50, which has a similar slope but younger plants aged 10 years, as well as SLH-45, which has a slope of 3% and plants that are 9 years old; neither of these plantations shows SOC levels significantly different from those in other locations (Table 3). In comparison, SOC levels in oil palm plantations in Bengkulu and West Java, with plant ages ranging from 5 to 25 years, indicate that the SOC in the 0-10 cm layer falls between medium to high (3.38% to 4.47%), while the SOC in the 10-30 cm layer is categorized as low to medium (2.49% to 3.13%) (Handayani *et al*., 2024).

Table 3: SOC and bulk density below smallholders' oil palm plantations in Suka Maju Village

HLU	Slope (%)	Age of oil palm (years)	SOC (%) at depth			Bulk density (g/cm^3) at depth		
			0-10 cm	10-30 cm	30-60 cm	0-10 cm	10-30 cm	30-60 cm
HLU-45	2	11	2.33 ab	1.86	1.43	1.21	1.29	1.35
HLU-45	3	9	1.62 b	1.17	1.16	1.27	1.43	1.56
HLU-46	4	7	2.53 ab	2.06	0.93	1.21	1.30	1.45
HLU-46	6	10	1.73 ab	1.34	0.87	1.23	1.27	1.37
HLU-46	7	20	3.62 a	2.15	1.58	1.17	1.31	1.35
HLU-46	8	20	3.57 a	2.36	1.07	1.13	1.30	1.32
HLU-47	9	7	1.69 ab	1.29	1.08	1.21	1.23	1.36
HLU-49	3	10	2.76 ab	1.93	1.55	1.27	1.33	1.37
HLU-50	8	10	1.62 b	1.46	1.12	1.26	1.35	1.42
HLU-51	10	15	2.72 ab	2.29	1.28	1.24	1.31	1.43
Average			2.33	1.86	1.43	1.21	1.29	1.35

SOC <1% very low; 1-2 % low; 2-3 % medium; 3-5 % high; > 5% very high, BD <0.66 g/cm^3; 0.66-1.44 g/cm^3 medium; > 1.44 g/cm^3 high; Numbers followed by the same letter indicate an insignificant difference (p = 0.05; DNMRT = 2.39)

Soil organic carbon is a key component of soil organic matter (SOM), which is formed from materials produced by living organisms that decompose (Clara *et al*., 2017). SOM includes a mix of plant and animal residues, as well as humus. Dead organic matter, mainly from plants, enters the soil through soil fauna and is transformed into carbon by microorganisms (Bot and Benites, 2005). SOC levels are generally higher in the upper soil layers, where organic sources like fallen leaves, twigs, and roots are found, and lower in deeper layers. Under oil palm stands, sources of SOC include dried fronds, undergrowth, litter, and decaying roots, contributing to the upper soil layers (Hoorman and Reeder, 202; Both and Benites, 2005; Clara *et al*., 2017).

The area with the highest SOC features the oldest plants, which are approximately 20 years old and situated on slopes of 7% to 8%. This high SOC is largely due to the extensive surface cover provided by larger and wider plant canopies, as well as the presence of undergrowth and a nutrient-rich litter layer. As depicted in Figures 1e and 1f, nearly the entire soil surface in both gardens is covered with a variety of species of weeds, which contribute to soil fertility. Some areas are also covered with scattered dry fronds. This coverage protects the soil from direct sunlight, helping to maintain lower soil temperatures and preserve soil moisture. In contrast, high soil temperatures arising from exposed soil surfaces accelerate the decay of organic matter, leading to diminished organic content (Dharmawan, 2010). This phenomenon is evidenced in areas with lower SOC, such as gardens with a 4% slope and approximately 7-year-old plants (Figure 1c) or a 6% slope with 10-year-old plants (Figure 1d), where the soil surface is largely free of weeds and plant residues. Soil organic matter mainly consisting of SOC, significantly influences soil density as indicated by bulk density (BD) values (McKenzie, 2010). BD is lowest in the topsoil (0-10 cm) at 1.13 to 1.27 g/cm^3, slightly higher in the 10-30 cm layer (1.23 to 1.43 g/cm^3), and highest in the 30-60 cm layer (1.32 to 1.56 g/cm^3). The low SOM content contributes to this variation. The pH is slightly acidic in the top two layers but becomes acidic in the 30-60 cm layer. SOM enhances cation exchange capacity (CEC) and nutrient availability, as lower SOM leads to declining pH. Overall, pH and BOT are crucial for soil fertility, with higher SOM levels improving both CEC and soil pH (see table 4).

Table 4: SOM and pH of soil under smallholders' oil palm plantations in Suka Maju Village

HLU	Slope (%)	Age of oil palm (years)	SOM (%) at depth (cm)			pH (H_2O) at depth		
			0-10 cm	10-30	30-60	0-10 cm	10-30 cm	30-60 cm
HLU-45	3	11	4.02[ab]	3.21	2.47	5.61	5.54	4.54
HLU-45	3	9	2.79[b]	2.02	2.00	5.54	5.50	5.21
HLU-46	4	7	4.36[ab]	3.55	1.60	*5.91*	5.53	5.16
HLU-46	6	10	2.98[ab]	2.31	1.50	5.43	5.51	4.70
HLU-46	8	20	6.24[a]	3.71	1.00	*6.07*	5.68	4.61
HLU-46	8	20	6.15[a]	4.07	1.84	6.14	*5.95*	5,04
HLU-47	9	7	2.91[b]	2.22	1.86	5.49	4.65	4.29
HLU-49	3	10	4.76[ab]	3.33	1.67	5.*78*	5.28	5.13
HLU-50	8	10	2.79[b]	2.52	1.93	5.45	5.17	4.39
HLU-51	10	15	4.69[ab]	3.95	2.21	5.59	5.58	4.54

SOM <2% very low; 2-3.99 % low; 4-9.99 medium; 10-20 % high; > 20 % very high; pH < 5.5 acid; 5.5-... slightly acid; 5.5 -... Numbers followed by the same letter indicate an insignificant difference (p = 0.05; DNMRT = 2.39)

Effective soil management that maximises surface cover from the canopy, understorey, and litter will help maintain high SOM content and regulate the weathering process. The SOM content can vary and is influenced by land use and management practices, which affect the sources of organic matter and its weathering (Islam and Weil, 2000). Vegetation continuously provides maximum surface cover through fallen leaves and twigs that remain on the soil surface, whether they are intact, decayed, or decomposed (Hairiah *et al*., 2004).

Soil Carbon Organic Stock

SOC (Soil Organic Carbon) stocks beneath smallholder oil palm stands in Suka Maju The village's slopes of 3 to 10% show that plants aged 7 to 20 years have SOC stocks ranging from 20.34 to 42.35 tons per hectare at 0-10 cm depth. These levels are higher than those in the 10-30 cm layer (27.61 to 61.36 tons/ha) and the 30-60 cm layer (37.19 to 63.99 tons/ha). In HLU-46, with 20-year-old plants on 7-8% slopes, SOC stocks in the upper layer were significantly greater than in HLU-50 and HLU-47, which have younger plants. This suggests that SOC stock increases with plant age, even on steeper slopes. SOC stock and content decline as soil depth increases, influenced primarily by plant age, condition, and soil cover (see table 1). Older plants create larger canopies, protecting the soil from sunlight and erosion, while high temperatures accelerate organic decomposition, reducing SOM. Heavy rainfall damages soil aggregates, leading to erosion and loss of nutrients. In HLU-46, SOC and SOM are notably higher in the top layer (0-10 cm) with a slope gradient of 7-8% and 20-year-old plants compared to those with a smaller slope gradient.

Table 5: Soil organic carbon (SOC) storage on slopes of 2-10 % with a plant age of 7-20 years under oil palm stands in Suka Maju Village, Muaro Jambi Regency

HLU	Slope (%)	Age of the plant (years)	SOC stock (ton/ha) at depth		
			0-10 cm	10-30 cm	30-60 cm
HLU-45	3	11	28.28[abc]	47.13	37.19
HLU-45	2	9	20.68[bc]	33.17	53.05
HLU-46	4	7	29.05[abc]	51.02	39.49
HLU-46	6	10	21.51[bc]	34.13	35.84
HLU-46	7	20	42.35[a]	56.33	63.99
HLU-46	8	20	40.34[a]	61.36	42.37
HLU-47	9	7	20.34[c]	27.61	44.54
HLU-49	3	10	35.05[abc]	51.34	63.71
HLU-50	8	10	20.43[bc]	39.43	47.41
HLU-51	10	15	33.95[abc]	60.16	54.16

Numbers followed by the same letter indicate an insignificant difference (p = 0.05; DNMRT = 2.39)

SOC stocks in the 0-10 cm layer were higher than in the 10-30 cm layer and significantly greater than in the 30-60 cm layer. Soil carbon storage at 0-30 cm ranged from 52.18 to 93.73 tons/ha, while the 30-60 cm layer had 36.39 to 63.71 tons/ha. Total SOC stock at 0-60 cm varied from 91.48 tons/ha (slope gradient 6%, plant age 10 years) to 162.67 tons/ha (slope gradient 7%, plant age 20 years) (Figure 2). SOC stock is less influenced by flat slopes than by plant age, which affects soil cover and contributions from plant residues (see table 5).

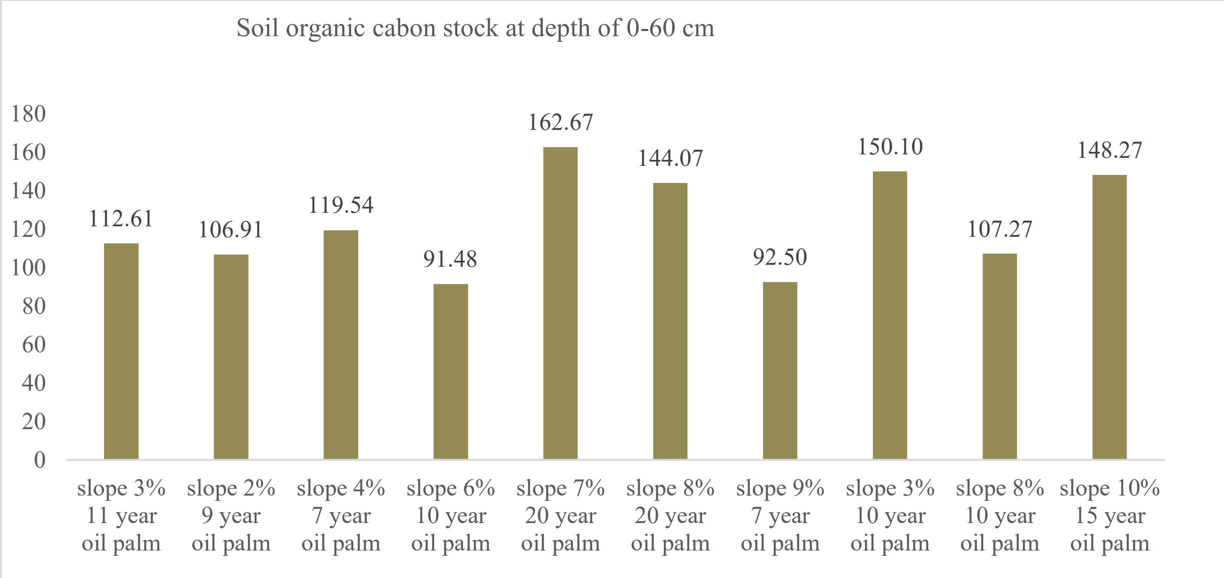

Figure 2: Soil organic carbon storage at a slope of 3-8% below the stand smallholders' oil palm aged 7-20 years in Suka Maju Village, Muaro Jambi Regency

Figure 2 shows that SOC stocks exceed 100 tons/ha on land with crops older than 10 years, while SOC stocks are less than 100 tons/ha on land with crops less than 10 years old. In this case, the negative impact of the slope can be mitigated by high vegetation and litter cover. Similar to SOC stocks on smallholder coffee plantations in Jangkat District, Merangin Regency, with gently sloping to very steep topography, SOC stocks vary from 66.05 tons/ha to 78.91 tons/ha. The highest SOC stocks are found on very steep land (slope gradients of 45-65%) due to the maximum land cover by vegetation, plant debris, and litter (Henny *et al*., 2024).

Table 6: Soil organic carbon stock at a depth of 0-60 cm under 7-20 years old oil palm stands in Suka Maju Village, Muaro Jambi Regency

HLU	Slope (%)	Age of oil palm (years)	Area (ha)	SOC stock (ton/ha)	Total SOC stock (ton)
HLU-45	0-3	9 and 11	302.3	109.75	33,177.43
HLU-46	3-8	7,10, and 20	440.2	129.44	56,979,49
HLU-47	8-15	7	107.3	96.24	10,326.55
HLU-49	0-3	10	16.8	150.50	2,528.68
HLU-50	3-8	10	38.7	107.54	4,161.80
HLU-51	8-15	15	11.2	148.27	1,660.62
Total			916.5		108,834.57
Average				118.62	

High soil organic carbon (SOC) content enhances physical, chemical, and biological properties, leading to increased soil fertility (Clara *et al*., 2017; Bot and Benites, 2005). The amount of carbon stored in the soil is influenced by the diversity and density of plants and crops, as well as their management practices. Greater soil fertility results in higher carbon storage (Hairiah and Rahayu, 2007). In Suka Maju Village, the total SOC stock in a smallholder oil palm plantation covering 916.5 hectares was 108,834.57 tons, averaging 118.75 tons per hectare (see Table 6). According to Agus *et al*. (2011), the SOC stock at a depth of 0-100 cm in dry land typically ranges from 20 to 300 tons per hectare, with the majority concentrated in the top 0-30 cm layer. At depths greater than one meter, SOC stock is very low and often negligible.

5. CONCLUSION

The soil organic carbon stock varied between 91.48 and 150.50 tons per hectare. SOC levels were greater than 100 tons per hectare on land with plants older than 10 years, while levels were below 100 tons per hectare on land with plants younger than 10 years. The highest SOC stock, recorded at 150.50 tons per hectare, was found on land with a slope of 7% and a plant age of 20 years. Among the 19 identified understorey plant species, four have significant potential for green fodder. *Asystasia gangetica*, one of these species, is commonly found across nearly all land units, with a distribution range of 35% to 84%. It is particularly dominant in areas with a plant age of 20 years, which are the oldest in this study.

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