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Estimation of carbon stock in tea plants (*Camellia sinensis*) based on age variation at Tambi plantation unit

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ABSTRACT
Background: As an effort to reduce current climate change, conservation measures such as carbon stock measurements are needed. Tea plants are a suitable commodity for transforming towards low carbon production because perennial plants such as can absorb and store more carbon than seasonal agricultural crops. **Methods**: Sampling was carried out using a random sampling method that was taken randomly to represent a population for each block number. Data collection for the study was carried out by taking 3 soil and plant samples at each age of the tea plant with an age of 10 years, 30 years, 40 years, and 100 years. The plant samples taken were leaves, stems, roots, and litter. The soil samples taken were soil with a depth of 0-10 cm, 10-20 cm, and 20-30 cm with disturbed and undisturbed soil sampling. **Findings:** The total carbon stock value of tea plants stored in the Pemandangan Block UP Tambi is 63.17 tons/ha in 10-year-old tea plants; 67.26 tons/ha in 30-year-old tea plants; 67.87 tons/ha in 40-year-old tea plants; and 69.40 tons/ha in 100-year-old tea plants. After analyzing the relationship between physical and chemical properties of soil with biomass carbon reserves, C-Organic, soil texture, and soil volume weight are the parameters that most influence carbon reserve content. **Conclusion**: Plant age due to replanting and pruning, making them unsuitable for soil carbon stock estimation. **Novelty/Originality of this article:** This study offers novelty by integrating field-based carbon stock measurements of tea plants with variations in plant age and Sentinel-2A remote sensing analysis, providing a unique contribution to understanding the relationship between soil properties, biomass, and carbon storage capacity in tea plantations, which has not been extensively explored in previous research.

KEYWORDS: carbon stock; sentinel-2a imagery; tea plant.

1. Introduction

Climate change has become an important issue for human life today as it is closely related to socio-environmental transformations. The continuous increase in the concentration of carbon dioxide and other greenhouse gases has led to global warming and climate change (Watson et al., 2020). In 2022, global carbon dioxide emissions from fossil fuels and industry reached 37.15 billion metric tons ($GtCO_2$) and were projected to increase by 1.1% in 2023, hitting a record high of 37.55 $GtCO_2$. Overall, global CO_2 emissions have increased by more than 60% since 1990 (Ian Tieso, 2024). One approach to reducing carbon emissions through the REDD (Reducing Emissions from Deforestation and Forest Degradation) scheme is the MRV (Measurable, Reportable, and Verifiable) system, which documents, reports, and verifies changes in carbon stock transparently, consistently, comparably, completely, and accurately (Hairiah et al., 2011). Advances in remote sensing technology with image-based approaches have enabled the prediction of biomass and carbon stock estimation, and one of the satellite images commonly used for forest biomass

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and carbon estimation is Sentinel-2A with a spatial resolution of 10 meters. Higher-resolution imagery can capture smaller land features, thereby improving the accuracy of the digitization process (Boyle et al., 2014).

Tea plants absorb carbon dioxide from the atmosphere through photosynthesis and store it in the form of biomass distributed in roots, stems, leaves, and litter (Pang et al., 2019). According to Hardjo et al. (2014), the average carbon stock of tea in PT Pagilaran plantations is 32.8 tons C/ha, while research conducted by Haryadi (2005) reported that tea plantations in the Gunung Halimun National Park area stored 22.13 tons/ha. Prayoga (2021) estimated the carbon stock in Kerinci tea plantations using Sentinel-2A imagery, which amounted to 1.33 tons/ha. Another study by Zhang et al. (2013) found that the average carbon stock in tea plantations in China ranged from 28.02 to 31.31 tons C/ha, while carbon stock measurements in tea-based agroforestry plantations in Northeast India at ages 6, 14, and 22 years were 44.8 ± 1.3, 50.2 ± 4.6, and 56.7 ± 4.9 Mg C/ha, respectively. This study concluded that tea-based agroforestry systems play an important role in carbon sequestration and storage, thereby contributing to climate change mitigation in Northeast India (Kalita et al., 2016).

Soil carbon storage has been recognized as one of the key strategies for climate change mitigation. In addition to its role in climate mitigation, sustainable and well-managed soil carbon storage under conservation practices can be maximized to support biodiversity and improve the physical, chemical, and biological fertility of soils. Increasing soil carbon storage enhances soil organic matter, which significantly influences soil properties. According to Krull et al. (2004), soil carbon contributes to pedological development that stabilizes soils against erosion, facilitates greater water infiltration, and forms organic matter that supports cation exchange and pH buffering capacity. Soil carbon stocks also serve as a major determinant of biological activity, as the diversity and activity of soil fauna and microorganisms are directly linked to organic matter (Siringoringo, 2014).

Tea, as a perennial crop, is considered a suitable commodity for transitioning toward low-carbon production because it can absorb and store more carbon compared to annual crops (FAO, 2022). The age variations of tea plants in PT Tambi Tea Plantation are expected to influence plant biomass and ultimately the stored carbon stock. Therefore, this study aims to estimate the carbon stock across different tea plant age classes. The application of satellite imagery is highly relevant as a research basis for estimating biomass and carbon stocks in the Tambi Plantation Unit, particularly in the Pemandangan Block.

The phenomenon of global warming has become increasingly alarming, demanding global efforts to reduce greenhouse gas (GHG) emissions. In 2019, approximately 22% of global GHG emissions, equivalent to 13 gigatons of CO_2, originated from the agriculture, forestry, and other land use (AFOLU) sectors (IPCC, 2023). The lack of comprehensive data affects the effectiveness of climate change mitigation strategies, and challenges remain in integrating carbon stock data with sustainable natural resource management policies and practices. Therefore, further research is needed to identify and understand in greater depth the components that significantly influence carbon stocks, and the development of reliable methods is essential to measure and monitor carbon stocks efficiently.

In efforts to mitigate current climate change, studies on carbon stocks in tea plants are required. Tea has been considered an agricultural crop capable of storing carbon, yet many questions and uncertainties remain regarding its carbon storage capacity under different conditions. This is primarily due to the limited understanding and insufficient experimental studies that assess how effectively tea plants can store carbon under diverse land management practices, cultivation techniques, and soil types. Moreover, the capacity for carbon sequestration and related emissions may be influenced by changes in tea plantation management systems, such as production intensification and land-use modifications. Tea is recognized as a commodity with the potential to reduce atmospheric emissions, and FAO (2022) identifies tea as a suitable crop for transitioning toward low-carbon production systems. Depending on the plantation, tea production typically generates between 0.4 and 1.5 tons of CO_2 per ton of processed tea (Zhu et al., 2017). These figures are also influenced by additional factors such as fertilizer application, transportation of harvested plants, and energy consumption during processing. However, the emissions produced are offset by the substantially greater amount of carbon absorbed by tea plants. As a perennial crop, tea is capable of absorbing and storing more carbon than annual crops, and the carbon remains sequestered in plant biomass and soil organic matter as long as the plants are not felled or decomposed. Furthermore, tea cultivation does not require intensive land tillage, thereby maintaining the stability of carbon stored in the soil. Carbon stock measurements are therefore necessary to provide data on the amount of carbon stored within a plantation, which can then be used to assess the capacity of tea plants and soils in the Pemandangan Block of the Tambi Plantation Unit to sequester carbon.

2. Methods

The research involved direct field observations, soil sampling at different tea plant ages using auger and ring methods, collection of tea plant components such as leaves, stems, and roots, litter sampling, laboratory analysis of soil and vegetation, primary data processing, and the preparation of the final report. Data collection began with soil and plant sampling using the random sampling method, which was applied to ensure that every element of the population had an equal chance of being selected. The determination of sampling locations was based on secondary data containing block numbers and plant ages in the Pemandangan Block, where tea plants aged 10 years were located in block number 8, 30 years in block number 3, 40 years in block number 6, and 100 years in block number 4. For each plant age category, soil samples were collected at three points and from every soil layer at depths of 0–10 cm, 10–20 cm, and 20–30 cm, resulting in 36 total soil samples that were then composited by age category.

2.1 Measurement of biomass carbon stock (tea plants and litter)

In tea plants, the destructive method was applied by uprooting the entire plant, including the stems, leaves, and roots. The mixture of stems, leaves, and roots was then weighed to obtain the fresh weight, with a subsample of 300 grams taken. The plant subsamples were dried at a temperature of 85°C for 48 hours in an oven until a constant weight was reached. The dried plant samples were then weighed to determine the dry weight, and the carbon stock of tea plants (leaves, stems, and roots) could be calculated after the dry weight was obtained using the following equation 1.

$$Ctn = BK \; x \; Fraction \; C \qquad \text{(Eq.1)}$$

In this study, the carbon stock of tea plants (Cs) is expressed in tons per hectare (ton/ha). The calculation is based on the dry weight of biomass (DW), measured in kilograms, which represents the plant's total dry matter. To estimate the carbon content, a conversion factor known as the carbon fraction is applied, with a standard value of 0.47. This fraction indicates that approximately 47% of the plant's dry biomass consists of carbon. Dead organic matter includes parts of tea plants that have fallen such as leaves and twigs located on the soil surface but have not undergone decomposition. Sample collection was carried out in a 1 m × 1 m plot beneath the tea plant canopy, and the fresh weight was then measured. The samples were dried at a temperature of 85°C for 48 hours in an oven until a constant weight was obtained. The calculation of carbon from dead organic matter was carried out using the following equation 2 (BSN, 2011).

$$Cs = BKs \; x \; 0.47 \qquad \text{(Eq.2)}$$

Furthermore, the total carbon content of tea plants and litter per hectare was calculated using the following equation 3. In this research, the organic carbon content of litter is represented by Ct, measured in kilograms. The parameter Lplot refers to the plot area in each carbon pool, expressed in square meters (m^2). From these values, the Cs variable is calculated, which denotes the carbon content per hectare in each carbon pool for every plot, expressed in tons per hectare (ton/ha). This framework allows for the standardization of measurements across different plots, making it possible to compare and analyze carbon stocks at the landscape level.

$$Cs = \frac{Ct}{1000} VS \frac{1000}{Lplot} \quad \text{(Eq.3)}$$

2.2 Measurement of soil carbon stock

Using the formula referring to the National Standardization Agency (2011), namely equation 4. In this study, the soil organic carbon content (Ct) is expressed in grams per square centimeter (g/cm^2), serving as a key parameter in assessing soil carbon stocks. The soil solum depth (Kd), measured in centimeters (cm), represents the vertical extent of the soil layer considered in the analysis. Meanwhile, the bulk density (BV) of the fine soil fraction (<2 mm) is recorded in grams per cubic centimeter (g/cm^3), reflecting the compactness and weight of the soil particles. Finally, the percentage of soil organic carbon (%C-organic) provides the proportion of organic carbon present in the soil relative to its total composition, offering insights into soil fertility and carbon storage capacity.

$$Ct = Kd \ x \ BV \ x \ \%C \ Organic \quad \text{(Eq.4)}$$

In the book written by Rusolono et al. (2015), in order to obtain the value of carbon stock at each soil depth (Ct) in units of ton/ha, a conversion process must be carried out. The unit of soil organic carbon content (COt) needs to be converted into "ton C/ton," while the bulk density of the soil, which is obtained from the multiplication of soil depth (Kd) and bulk volume (BV), must be converted into "ton/ha." After these conversions are made, the total soil carbon stock up to a certain depth is calculated by summing the carbon stock values at each respective soil depth. This procedure ensures that the estimation of soil carbon stock is expressed in a standardized form and can be compared across different soil layers as well as research sites.

2.3 Measurement of total carbon stock

The calculation refers to the formula established by the National Standardization Agency (BSN, 2011), as follows equation 5. In this study, the total carbon stock (Ctotal), expressed in tons per hectare (ton/ha), represents the overall amount of carbon stored in both biomass and soil components. The carbon stock per hectare of biomass (Cn), also measured in tons per hectare, specifically refers to the carbon contained within plant biomass. Meanwhile, the organic soil carbon stock per hectare (Ct) denotes the amount of carbon stored in the soil, highlighting its contribution to the total carbon storage capacity of the ecosystem.

$$Ctotal = Cn(Ctn + Cs) + Csoil \quad \text{(Eq.5)}$$

2.4 Soil sample preparation and analysis methods

The soil samples collected from each sampling point were prepared through air-drying. After the air-drying process was completed, the samples were sieved using mesh sizes of 2 mm and 0.5 mm. The sieved soil samples were then placed into plastic bags, labeled accordingly, and made ready for subsequent laboratory analysis. The soil sample analysis was conducted at the Laboratory of the Department of Soil Universitas Gadjah Mada. The analysis used air-dried soil samples with diameters of 2 mm and 0.5 mm from disturbed soil, and furthermore, the ring method was applied to undisturbed soil samples. The physical and chemical analyses that were carried out included the following. For the physical analysis of soil, the determination of soil texture was performed using the pipette method (Soil Research Institute, 2022), and the determination of bulk density was carried out using the Ring method (Soil Research Institute, 2022). Meanwhile, for the chemical analysis of soil, the determination of soil acidity (pH H_2O and pH NaF) was conducted using a pH meter (Soil and Fertilizer Research Institute, 2023). The determination of soil organic carbon was carried out using the Muffle Furnace method (Soil and Fertilizer Research Institute, 2023), and finally, the determination of cation exchange capacity (CEC) was also performed (Soil and Fertilizer Research Institute, 2023).

2.5 Remote sensing data processing

The imagery used in this study was obtained from Sentinel-2A satellite images sourced from the official Copernicus Data Space website. The imagery was captured over the research site at the PT Tambi tea plantation on October 28, 2023. The selection of satellite imagery on this date was based on its low cloud cover percentage of 9.3%. The use of imagery with a low percentage of cloud cover facilitates image processing because it does not require a cloud masking process. The Sentinel-2A imagery used in this study did not undergo geometric correction because Sentinel-2A imagery at Level 1C is already geometrically corrected (European Space Agency, 2015). Radiometric correction was also not required, as Sentinel-2A imagery has already been corrected and provides Bottom of Atmosphere reflectance values (Gatti & Bertolini, 2015).

3. Results and Discussion

3.1 Analysis of soil properties (physical & chemical) at different plant ages

The results of the analysis of soil physical and chemical properties were obtained from tea plants aged 10, 30, 40, and 100 years. However, the variation in tea plant age examined in this study loses its relevance, as it disregards the periodic pruning of tea shoots that occurs every four years. Therefore, future research should conduct more detailed profiling of the research objects, including the physical conditions, growth processes of tea plants, and the characteristics of soil physical and chemical properties.

The soil texture showed values ranging from 16–20% for the clay fraction, 56–67% for the silt fraction, and 17–28% for the sand fraction, classifying the soil texture as silty clay loam. The bulk density of the soil samples ranged from 0.56 to 0.69 g/cm^3. Soil pH, consisting of pH H_2O with a range of 4.7–5.6, was categorized as acidic to slightly acidic, while pH NaF ranged from 10.33 to 11.68. The organic carbon content ranged from 8.45–11.74%, which falls into the very high category. The soil cation exchange capacity (CEC) ranged from 8.71–16.20 cmol(+)/kg, categorized as low.

Table 1. Mean values of soil laboratory tests at several sampling points

Age	Depth (cm)	Texture (%)			Bulk Density	pH		Organic C	CEC
		Clay	Silt	Sand	(g/cm^3)	H_2O	NaF	(%)	(cmol(+)/kg)
10 years	0-10	16	56	27	0.64	4.65	11.40	9.52	10.23
	10-20	16	56	28	0.65	5.21	11..43	8.65	8.71
	20-30	15	59	26	0.69	5.27	11.48	8.45	12.08
30 years	0-10	17	60	22	0.59	4.71	11.30	10.92	11.77
	10-20	16	62	22	0.64	4.88	11.40	9.73	11.63
	20-30	15	66	19	0.66	5.69	11.68	9.15	10.79
40 years	0-10	12	67	21	0.56	5.37	10.33	11.74	14.33
	10-20	15	59	26	0.58	5.42	10.44	10.52	12.16
	20-30	15	67	17	0.61	5.24	11.25	10.04	11.85
100 years	0-10	20	61	19	0.57	4.93	11.00	11.25	16.20
	10-20	19	64	17	0.59	5.24	11.30	10.68	14.31
	20-30	16	65	19	0.64	5.60	11.41	9.85	10.62

The classification and determination of soil physical and chemical properties were based on the assessment criteria from the Technical Guidelines for Soil Chemistry, Water, and Fertilizers (2023). The average values of soil laboratory tests from several sampling points are presented in Table 1.

3.1.1 Soil texture

Soil texture is a physical property of soil that provides a descriptive representation of the particle size composition of soil constituents, which are classified into three main groups. Soil texture distinguishes the proportion of clay, silt, and sand fractions in a soil mass. The sand fraction has a particle diameter ranging from 2–0.05 mm. The clay fraction has a much smaller particle size, less than 0.02 mm. The soil fraction with particle sizes between 0.02–2 mm is referred to as the silt fraction (Sartohadi et al., 2022). Soil texture is an important characteristic that influences soil water, biological, chemical, fertility, erosion, microtopography, workability, aeration, and soil climate properties (Liebens, 2001). To date, soil texture has been regarded as a critical control factor for a number of soil processes, including structure development, carbon sequestration, nutrient retention (e.g., N), and water infiltration and storage (Xia et al., 2020). The determination of soil texture is commonly conducted using a graphical method, in which the proportions of sand, silt, and clay are plotted on a soil texture triangle. This diagram is divided into several unit areas that define various texture classes, and the soil is assigned a texture class based on the area in which the sample is plotted. The soil texture graph at different soil depths and plant ages is presented in Figure 1.

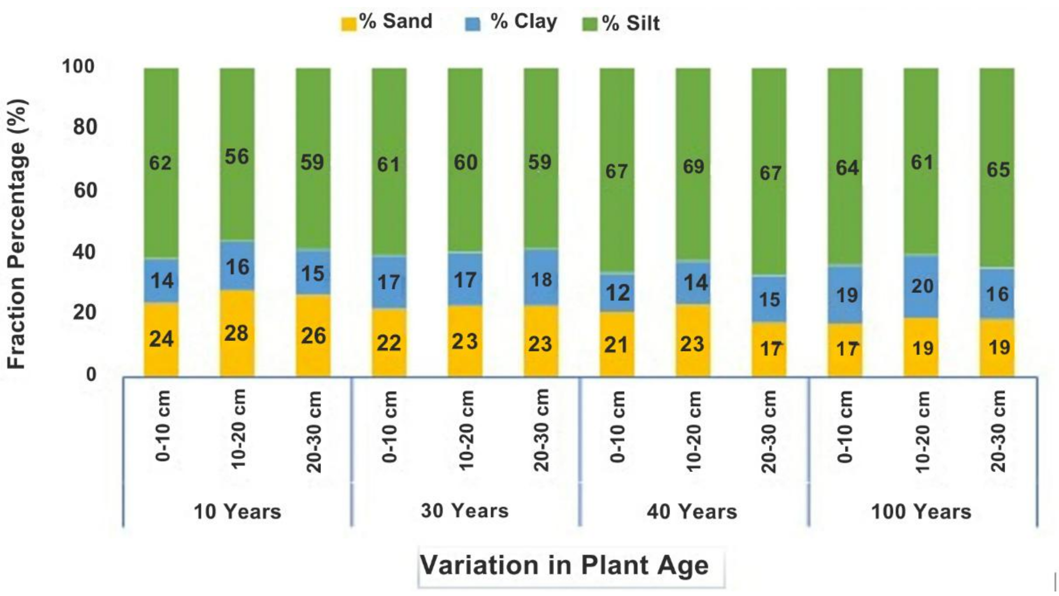

Fig. 1. Soil texture at different soil depths and plant ages

The percentage of sand, silt, and clay fractions in the soils of UP Tambi ranged from 16–20% for clay, 67–56% for silt, and 17–28% for sand, indicating that the soils were dominated by a silty texture. This texture facilitated soil cultivation but could also become compact under wet conditions. The high silt content was influenced by volcanic ash deposits dominated by short-range order minerals such as allophane and imogolite (Ferdeanty et al., 2019; Sukarman & Dairiah, 2014). Soil texture at the study site showed no variation across soil depth and tea plant age, consistently classified as silt loam, which plays an important role in water retention and nutrient availability (Zurhalena & Farni, 2010; Mahmud, 2014).

The silt + clay fractions dominated the soil composition, reaching 72–82% across samples, while sand fractions were only 18–28%. This resulted in a high silt-to-clay ratio (3.4–4.3), particularly in the topsoil layer (0–10 cm), which was greater than in deeper layers. Similar findings were reported by Yakubu & Ojanuga (2013), who noted that topsoil generally exhibits higher silt-to-clay ratios due to the influence of weathering. In contrast, the lower subsoil ratios reflected silt weathering into clay and clay illuviation processes (Nwokocha et al., 2003). According to FAO (1990), such values indicate relatively young soils with limited development.

3.1.2 Soil bulk density

Bulk density is an indicator of soil compaction, defined as the mass per unit volume of dry soil, consisting of the volume of solid material and the volume of pore spaces between particles. Yulnafatmawita et al. (2007) stated that soils with high bulk density values can inhibit plant growth compared to soils with low bulk density, even when nutrient availability is sufficient. The physical properties of Andisol soils indicate that they typically have low bulk density, as they are primarily composed of fine amorphous volcanic ash. In addition, soil bulk density also affects soil porosity, where higher bulk density values result in lower total pore space (Shah et al., 2017). Therefore, bulk density plays an important role in estimating soil productivity, soil quality, and soil carbon storage (Al-Shammary et al., 2018). The graph of bulk density at different soil depths and plant ages is presented in Figure 2.

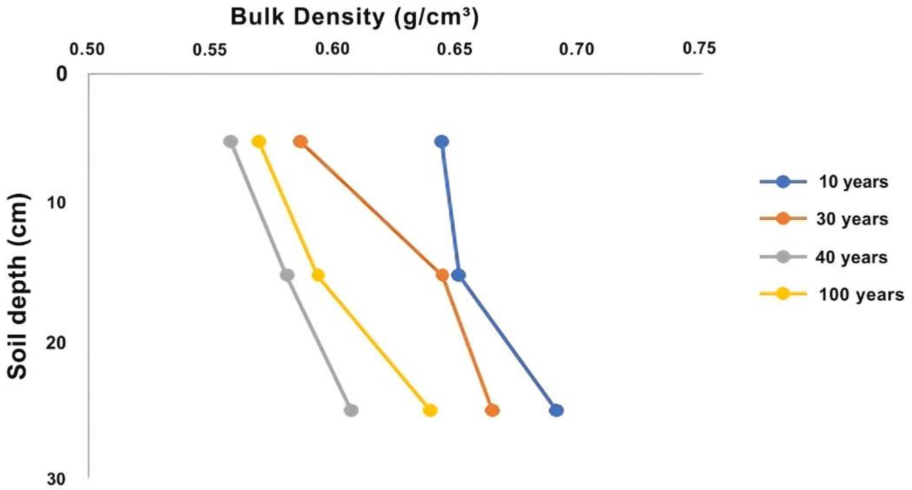

Fig. 2. Soil bulk density at different soil depths and plant ages

The average bulk density (BD) values at the study site were 0.66 g/cm^3 at 10 years, 0.63 g/cm^3 at 30 years, 0.58 g/cm^3 at 40 years, and 0.60 g/cm^3 at 100 years. These values indicate that the highest BD occurred in tea plants at 10 years of age. The higher BD compared to other plants was partly due to the size and strength of root penetration in 10-year-old plants, which were still not lower than those of older plants. Yusra et al. (2023) stated that bulk density is one of the indicators used to evaluate the possibility of roots penetrating the soil, and the older the plants, the greater and deeper the root penetration into the soil. This was evident in the BD values of this study, where BD decreased with increasing plant age. However, there was an increase in BD at 100 years, which occurred due to human activities such as walking on the soil surface. This was because the Scenic Block of UP Tambi, located in a tourist area, is one of the most frequently traversed sites, and pressure on the topsoil layer resulted in higher BD values.

The bulk density values of the soil at each depth and across different plant ages in the Scenic Block of PT Tambi ranged between 0.56–0.69 g/cm^3. According to Sukarman et al. (2020), these values fall into the low BD category because the soils at the research site were formed from volcanic ash. The highest to lowest BD values at the site were recorded in plants aged 40 years, 100 years, 30 years, and 10 years, respectively. The low BD values were strongly influenced by the dominant content of amorphous minerals, which increased the number of micropores, particularly intra- and inter-particles of allophane (Jurati, 2016).

Allophane particles are porous spherical structures with diameters of 3–5 nm, giving them a large specific surface area ranging from 400–900 m^2/g and high porosity (Nanzyo, 2022). The presence of amorphous minerals makes the soil more porous due to favorable aggregation processes.

The highest BD values for each plant age were found in the deepest soil layer (20–30 cm), ranging from 0.57–0.64 g/cm^3, and this was followed by consistent increases in BD with increasing soil depth. Bulk density is closely related to soil pore space, root penetration, microbial activity, and organic matter accumulation (Mansyur et al., 2023). This was confirmed in this study, where the lowest BD values were found in the surface layer due to limited root penetration of tea plants, which resulted in smaller soil pore spaces. In addition, the high organic matter content also contributed to lowering BD values, as the decomposition of various organic materials reduced soil bulk density and transformed dense soil structures into crumbly aggregates, making the soil easier to cultivate (Amanah & Taufik, 2021). Furthermore, high organic matter levels can convert micropores into mesopores, thereby improving soil aeration. This was evident in the present study, where soil organic matter and C-organic content were higher in the surface layers.

3.1.3 Soil acidity (ph) in H_2O and NaF

Soil acidity or pH is an indicator of soil acidity or alkalinity that reflects the physical and chemical properties of soil quality, and the actual pH value (H_2O) indicates the concentration of hydrogen ions (H^+) in the soil. Several factors influence soil pH, such as soil organic matter content, cation exchange capacity, and the soil clay fraction (Wang et al., 2014), and the pH (H_2O) of Andisol soils in Indonesia ranges from 3.8–6.4 (Arabia et al., 2015). Extremely acidic or alkaline pH values can affect the availability of nutrients in the soil, which may lead to nutrient imbalances in plants (Tsagaan et al., 2021), and according to Uthbah et al. (2017), soil pH indirectly influences the carbon stock stored in the soil. Meanwhile, NaF pH testing in Andisol soils is used to determine the presence of short-range non-crystalline minerals (allophane and imogolite), so the NaF pH value is influenced by the availability of non-crystalline minerals in the soil, and Andisol pH affects the overall soil depth. Soils with NaF pH values ≥ 9.4 indicate the presence of andic materials (allophane) that dominate the exchange complex, which is due to the relatively high amorphous allophane content in Andisols as indicated by high NaF pH values, and allophane minerals can form complexes with organic matter that protect it from decomposition. The values of soil pH H_2O and NaF at different soil depths and plant ages are shown in Figure 3.

The pH values at each soil depth and the age variations of tea plants in the Pemandangan Block of UP Tambi ranged from 4.65 to 5.69 for pH H_2O and from 10.33 to 11.68 for pH NaF. The pH H_2O values at the study site were classified as slightly acidic to acidic. According to Ririska et al. (2023), acidic and slightly acidic pH values are caused by vegetation that contributes organic matter through decomposed litter. The decomposition process usually decreases soil pH because it releases organic acids that lower soil pH (Ririska et al., 2023). In addition, high rainfall also causes intensive leaching of nutrients, and this is consistent with the site conditions and the andisol soil type that generally occurs in areas with relatively high rainfall.

The highest pH H_2O value was found in 30-year-old plants, which recorded 4.65, while the highest pH NaF value was 11.68. This is closely related to the presence of allophane minerals contained in the soil. Soil pH also plays a role in the formation of allophane minerals (Wada, 1989). Allophane does not form well in the upper horizon of the soil because the high accumulation of humus in the upper part causes Al released from mineral weathering to be complexed by humic substances, thereby inhibiting allophane formation. This is also supported by Fiantis et al. (2002), who stated that the availability of allophane minerals in the lower layer is greater than in the upper soil. Therefore, the increase in NaF pH in the lower layer will affect the level of acidity of soil pH H_2O.

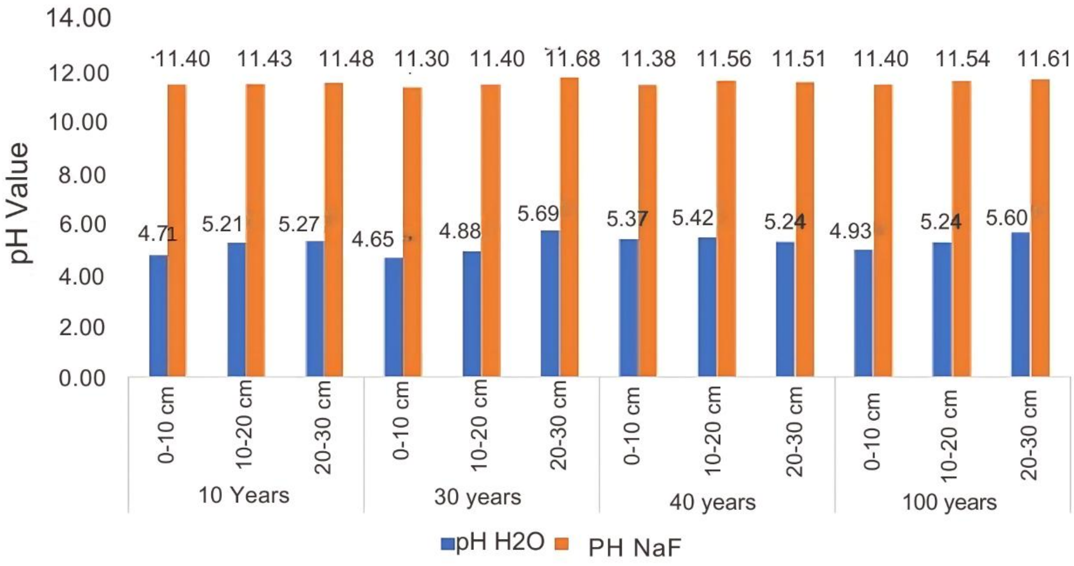

Fig. 3. Soil pH (H_2O and NaF) at different soil depths and plant ages

The pH H_2O values in the 0–10 cm layer at each age variation were 4.71 at 10 years, 4.65 at 30 years, 5.37 at 40 years, and 4.93 at 100 years, which indicates uniformity and a tendency to increase with soil depth. This occurs because the upper soil layer experiences more intensive mineral weathering compared to the lower soil. According to Basuki et al. (2018), this is due to higher concentrations of H+ and Al3+ ions in the upper soil layer formed from clay mineral weathering. Moreover, andisol pedogenesis occurs because of high Al and Fe levels, while acidic soils are generally dominated by Al, Fe, and Mn adsorption complexes (Ririska, 2023). The pH NaF values also showed consistency, with the highest levels found in the lowest layer (20–30 cm). The pH NaF values for 10-, 30-, 40-, and 100-year-old plants were 11.48, 11.68, 10.44, and 11.61, respectively, and the pH values of the lower layers tended to be higher than those of the upper layers. Ajidirman (2010) explained that the higher allophane content in the lower layers is due to the greater presence of active silanol (Si) and aluminum (Al). During the weathering process of andisol, primary minerals release cations that are leached, and Si ions are more easily leached than Al and Fe due to their higher mobility. The leached Si is transferred from the upper layer and accumulates in the lower layer (Ajidirman, 2010).

3.1.4 Soil organic carbon

Soil organic carbon, also known as soil organic C, originates from the decomposition of plants and animals and plays a crucial role in improving soil physical and chemical properties as well as enhancing fertility, productivity, and soil quality. The circulation of soil organic C also influences the carbon cycle and climate change (Rusdiana & Lubis, 2012). High levels of soil organic C can improve soil physical properties, increase soil biological activity, enhance the quality of mineral soils, and improve nutrient availability for plants, while the effect of soil carbon on global warming depends on the balance between carbon input into the soil and the increase in plant productivity. Moreover, the increase in soil organic C stock is influenced by the decomposition rate of plants, which occurs more rapidly at higher temperatures and more slowly at lower temperatures (Smith et al., 2008). In addition, Prasetyo (2005) reported that soil organic C levels in andisols in Indonesia range from 6–15%, and the values of soil organic C at different soil depths and plant ages are presented in Figure 4.

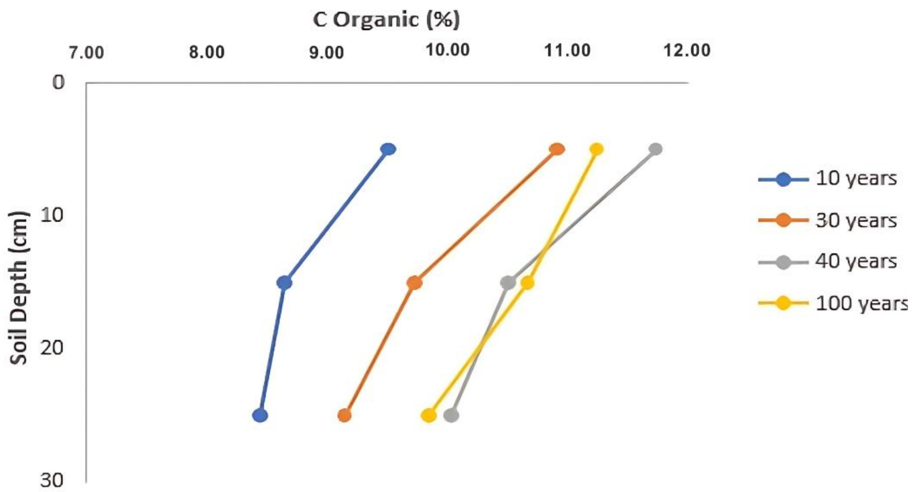

Fig. 4. Soil organic c values at different soil depths and plant ages

The percentage of soil organic carbon (C-Organic) at different plant ages showed the highest value consecutively at 40 years, 100 years, 30 years, and then 10 years. Tea plants aged 40 years had a C-Organic content of 10.77%, followed by 100 years with a slightly lower value of 10.59%, and then 30 and 10 years with 9.93% and 8.87%, respectively. Tea plants aged 10 years had the lowest C-Organic content compared to other plant ages because the litter contribution from younger tea plants to the soil was not as much as that from older plants, and litter is one of the main contributors of soil organic matter, especially in the upper layer. C-Organic subsequently becomes the main component of soil organic matter, while the C-Organic content in 40-year-old tea plants showed similarity to 100-year-old plants due to the higher canopy density in the 40-year-old block. A dense tea canopy can protect the soil from direct rainfall impact, thereby reducing the risk of soil erosion and organic matter loss (Aidil, 2020). Meanwhile, the higher C-Organic content in 100-year-old plants was due to the greater necromass contribution compared to other tea plants, and Mardiana et al. (2018) stated that biomass produced by necromass is greater than litter, which eventually becomes organic matter input to the soil.

The C-Organic values at each soil depth and plant age variation in the Pemandangan Block of UP Tambi ranged from 8.45–11.74%, and the C-Organic content in this study was categorized as very high. The high C-Organic content occurred because the soil order in the study area was Andisol, whose pedogenesis was formed from volcanic ash rich in minerals and high organic matter accumulation (Sukarmawati, 2011). Moreover, the decomposition of organic matter in Andisols is relatively slow due to the presence of amorphous aluminum hydroxide in cool air temperatures, and Andisols with good soil aeration and respiration also enhance microorganism performance to produce higher organic matter (Susilawati et al., 2013). The C-Organic values at different soil depths and plant ages in the study site showed relatively uniform results, in which the highest C-Organic content was in the upper layer and decreased with increasing soil depth, and this occurs because the surface layer has additional sources of organic matter from aboveground biomass such as litter and dead animals. The litter and animals on the soil surface then undergo decomposition to form humus that mixes with the topsoil (Basuki et al., 2018), and organic matter decomposition also occurs more rapidly due to climatic factors such as temperature, humidity, and oxygen, which are more favorable at the surface, thereby allowing microorganisms to work more optimally (Budhisurya et al., 2013).

3.1.5 Cation exchange capacity (CEC)

The cation exchange capacity (CEC), also commonly referred to as KPK, is the ability of soil to adsorb and exchange cations between the soil adsorption complex and the soil solution, expressed in cmol(+)/kg, and these cations are weakly adsorbed on the surfaces of mineral or organic colloids so that they can be released and exchanged again. The value of soil CEC is influenced by soil properties such as texture, organic matter, and the type of clay minerals (Ririska et al., 2023), and soil CEC can enhance the ability of soil to provide nutrients for plants in an available form, therefore soils with high CEC levels are capable of absorbing and supplying nutrients effectively (Rochman et al., 2020). Moreover, the CEC value of Andisol soils in Indonesia ranges from 6.5 to 52.0 cmol(+)/kg with categories ranging from very low to very high (Sukarman & Dariah, 2014), and the CEC values at different soil depths and plant age variations are shown in Figure 5.

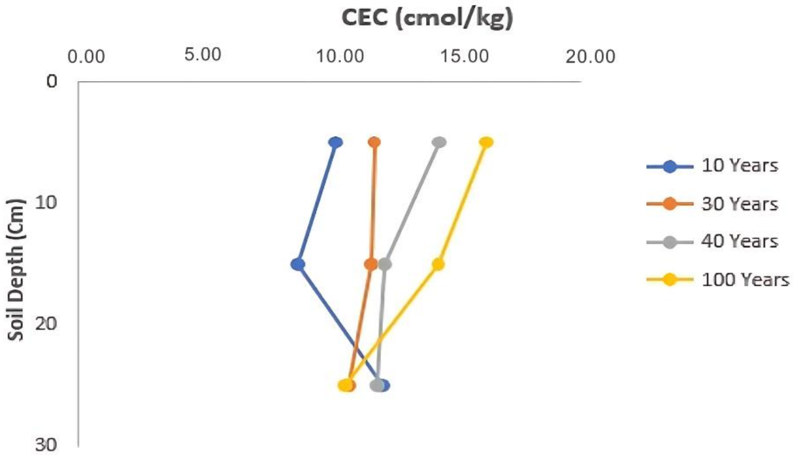

Fig. 5. Soil cation exchange capacity (CEC) values at different soil depths and plant ages

The average CEC values of soil at different tea plant ages of 10, 30, 40, and 100 years were 10.34 cmol/kg, 11.39 cmol/kg, 12.78 cmol/kg, and 13.71 cmol/kg, respectively. The highest CEC value in this study was found in 100-year-old plants, with 13.71 cmol/kg, and the soil CEC value consistently increased with plant age. This condition is indirectly related to the amount of biomass produced at each tea plant age, as 100-year-old plants produced more biomass compared to younger plants, which subsequently influenced the increase in organic matter and soil organic carbon (Bimsakti et al., 2017). Tea plants at 100 years of age had higher dead organic matter necromass compared to younger plants, indicating that soil biomass content and soil organic carbon were also higher, which was confirmed by the increasing soil organic matter with plant age.

The CEC values across soil depths and plant age variations in the Pemandangan Block of UP Tambi ranged between 8.71–12.16 cmol(+)/kg. The highest to lowest CEC values were observed in 100-, 40-, 30-, and 10-year-old tea plants, and the variation in CEC was determined by the content of clay and organic matter in the soil (Santi et al., 2023). Higher CEC levels allowed more cations to be adsorbed, while soil CEC also depended on the availability of clay minerals, organic matter content, and soil humus (Sahfitra, 2023). Since soil samples were taken from the same land type and at relatively close distances, the CEC values across plant age variations appeared relatively uniform. On the surface layer (0–10 cm), the CEC values were 10.23 cmol/kg for 10 years, 11.77 cmol/kg for 30 years, 14.33 cmol/kg for 40 years, and 16.20 cmol/kg for 100 years, and the highest CEC values were consistently found in the surface layer of each plant age, gradually decreasing with depth due to higher organic matter content in the topsoil. High organic matter in the upper layer increased soil negative charges, particularly from the dissociation of H+ ions in carboxyl (–COOH) and hydroxyl or phenolic (–OH) groups, thereby increasing soil CEC (Tisdale et al., 1999). Ramos et al. (2018) also emphasized that soil organic matter is one of the best soil colloids, with higher CEC potential compared to clay colloids.

The average CEC values at the study site ranked from highest in 100-year-old plants, followed by 40-, 30-, and 10-year-old plants, although the highest soil organic carbon was recorded at 40 years, followed by 100, 30, and 10 years. This occurred because the relationship between soil organic carbon and CEC is complex and influenced by several factors, including soil pH. Soil CEC levels were also affected by Na+ and H+ ions, which could alter CEC values without direct correlation to soil organic carbon content (Safitra, 2023). This was further supported by the average soil pH H_2O values, where 40-year-old plants recorded 5.34, while 100-year-old plants had a slightly lower pH of 5.26. Higher cation values indicated greater availability of base cations in the soil (Hasibuan, 2015).

3.2 Analysis of carbon stock at different ages of tea plants

Carbon stock is the amount of carbon stored on the soil surface as well as within the soil, where the above-ground carbon stock consists of plant biomass, litter, and necromass, while the below-ground carbon stock is soil organic matter. Soil physical and chemical properties and soil management can influence the amount of carbon stored in the soil (Haryati et al., 2014). In addition, plants as one of the carbon pools also play a major role in storing carbon stock, and the carbon stored in plants is accumulated in the form of biomass distributed in stems, leaves, and roots. Furthermore, the table of biomass carbon stock (plants and litter), soil carbon stock, and total carbon stock is presented in Table 2, while Figure 6 shows the biomass and soil carbon stock across different plant ages in the Pemandangan Block, UP Tambi.

Table 2. Biomass carbon stock (plants and litter), soil carbon stock, and total carbon stock

Plant Age	Biomass C-Stock (ton/ha)	Soil C-Stock (ton/ha))	Total C-Stock (ton/ha)
10 year	4.50	58.84	63.20
30 year	4.72	62.53	66.76
40 year	5.32	62.55	67.34
100 year	588	63.52	68.70

The carbon stock values at various plant ages in Blok Pemandangan UP Tambi ranged from 58.67–63.52 ton/ha from soil carbon stock, 4.50–5.88 ton/ha from biomass carbon stock, and 63.17–68.70 ton/ha from total carbon stock, and this indicates a consistency between biomass and soil carbon stocks where biomass carbon stock increases as soil carbon stock increases. Moreover, soil carbon stock refers to the amount of carbon stored within the soil body, biomass carbon stock represents the amount of carbon stored in plant biomass and litter, and total carbon stock is the sum of both soil and biomass carbon stocks.

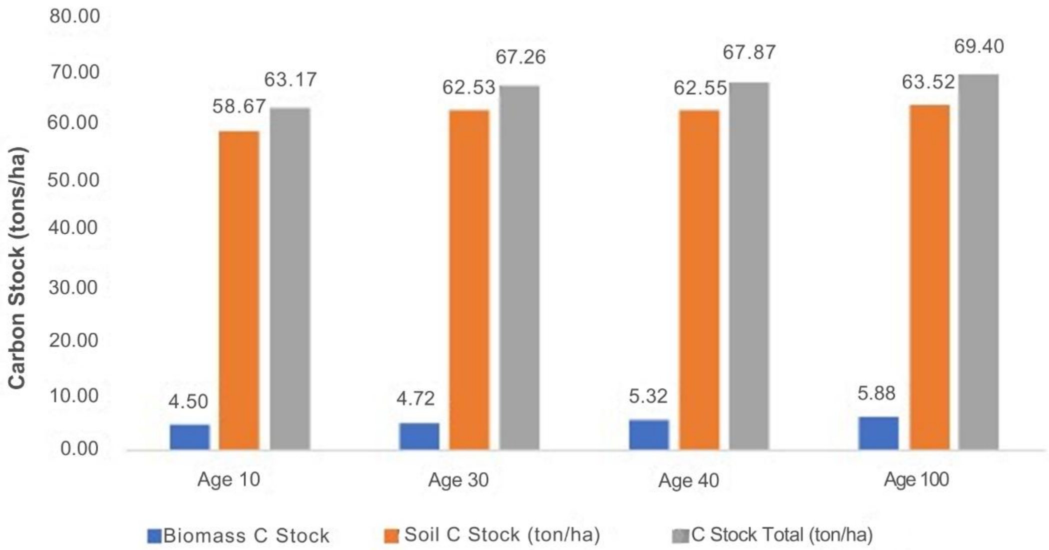

Fig. 6. Biomass and soil carbon stock at different plant ages in the Pemandangan Block, UP Tambi

The results also show that soil carbon stock has a much greater capacity compared to biomass carbon stock, since soil can store substantially more carbon than the cumulative stock in the atmosphere and vegetation, reaching more than 2000 Pg of carbon (C) at a depth of 100 cm in the topsoil (Gebrehiwot et al., 2018), and the figure of biomass carbon stock at each soil depth and plant age variation in Blok Pemandangan UP Tambi is shown in Figure 7.

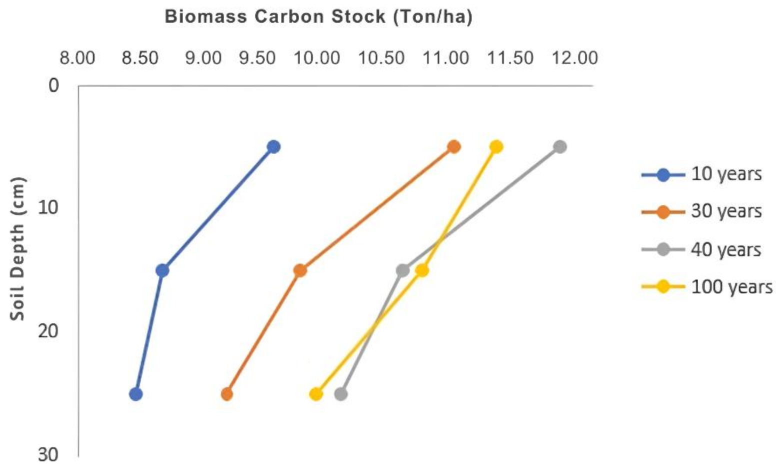

Fig. 7. Biomass carbon stock at different soil depths and plant ages in the Pemandangan Block

The biomass carbon stock (tea plants and litter) in Blok Pemandangan UP Tambi had values of 4.36 ton/ha at 10 years of age, 4.23 ton/ha at 30 years, 4.78 ton/ha at 40 years, and 5.73 ton/ha at 100 years in total, and these values indicate relatively uniform results, although plants at 100 years old had higher values compared to the younger ages. This occurred because the 100-year-old tea plantation research site contained more necromass than fallen leaves, where necromass refers to dead tree stems, and necromass contributes more carbon stock compared to dead plant leaves (Sorbu et al., 2021). Furthermore, Heriyanto et al. (2020) stated that the water content in each plant organ (stems, roots, branches, and leaves) directly affects the biomass or dry weight of each plant part, such as the lower water content in stems due to the higher proportion of wood-forming substances compared to other plant parts. These wood-forming substances fill the stem cell cavities with wood components rather than water, thus increasing the biomass weight (Widyasari, 2010).

The amount of carbon that can be stored by plants in the form of biomass is influenced by several factors such as tree species diversity, soil type, litter production, and plant age, which indirectly cause differences in the amount of carbon stock. Leaf area tends to increase with the age of the stand (Uthbah et al., 2017), and in this study, the larger the leaf area of tea plants, the greater the potential for CO_2 absorption. Putri & Wulandari (2015) also reported that a larger stem diameter in stands leads to greater biomass and carbon storage, as evidenced in this study where the diameter of tea plant stems increased with plant age, thereby enhancing the biomass and carbon stock. The figure of soil carbon at each soil depth and plant age variation in Blok Pemandangan UP Tambi is presented in Figure 8.

The carbon stock values at each soil depth and plant age variation in the Pemandangan Block of UP Tambi ranged from 58.84–63.52 ton/ha, and the values tended to be uniform, with the highest carbon stock found in the uppermost soil layer (0–10 cm), while the values decreased with increasing soil depth; soil carbon stock was proportional to soil organic matter and soil organic carbon (Akhbar & Arianingsih, 2016), thus proving that the high accumulation of organic matter in the topsoil largely originated from the decomposition of aboveground vegetation biomass. The total carbon stock content in the Pemandangan Block of UP Tambi was highest in 100-year-old tea plants at 69.40 ton/ha, followed by 40-year-old plants at 67.87 ton/ha, 30-year-old plants at 67.26 ton/ha, and 10-year-old plants at

63.34 ton/ha, indicating that the total carbon stock of tea plants increases with plant age, while stand density and pruning are also important factors in carbon storage, as Chen et al. (2013) concluded that routine tea pruning enhances the carbon storage capacity of tea plants, with older tea plants having the highest density and more frequent pruning for production purposes. The total carbon stock values of tea plants aged 100, 40, 30, and 10 years were 69.40 ton/ha, 67.87 ton/ha, 67.26 ton/ha, and 63.17 ton/ha, respectively, and the changes in total carbon stock between 100 and 40 years, 40 and 30 years, and 30 and 10 years were 0.03 ton/ha, 0.06 ton/ha, and 0.2 ton/ha, respectively; the rate of change in carbon stock was influenced by soil physical and chemical properties, such as soil organic carbon, bulk density, and soil texture, with significant differences in organic carbon content and bulk density between 30- and 10-year-old plants resulting in higher carbon stock changes compared to other age groups, thus indicating that greater differences in soil organic carbon and bulk density between plant ages will lead to greater changes in carbon stock rates.

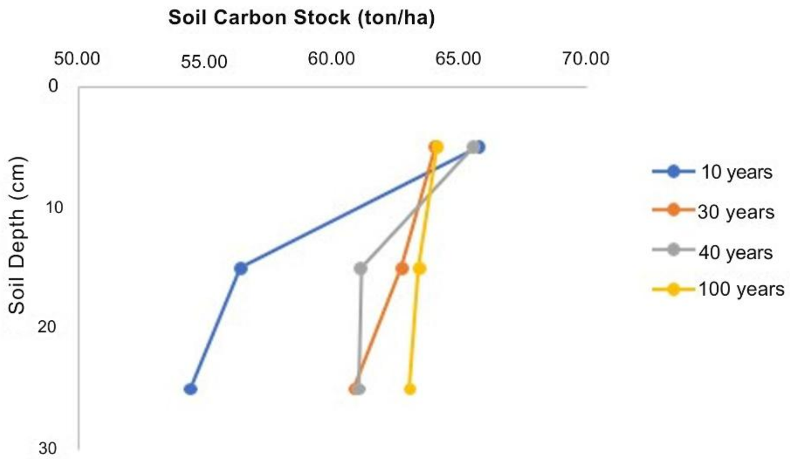

Fig. 8. Soil carbon stock at different soil depths and plant ages in the Pemandangan Block

3.3 Analysis of the relationship between soil physical and chemical properties and plant biomass carbon stock

Regression analysis is a statistical method used to measure the relationship between dependent and independent variables, and it is applied to determine the strength of the relationship and to predict the value of the dependent variable based on the independent variable. In regression analysis, it can be determined how far the independent variable influences the dependent variable and to make predictions based on this relationship. According to Basuki & Prawoto (2015), variable X represents the independent variable while variable Y is the dependent variable influenced by the independent variable, so both have a causal relationship, meaning that when the value of one variable increases, the other may also increase or inversely decrease. Regression analysis produces the R^2 value, or what is commonly referred to as the coefficient of determination, which indicates how well the regression analysis explains the variation in the dependent variable. The value of the coefficient of determination ranges from 0 to 100%, and the higher the coefficient of determination, the better the model explains the relationship between the independent and dependent variables. The polynomial regression analysis between soil organic carbon (C-Organic), bulk density, cation exchange capacity (CEC), pH, and texture with total carbon stock is shown in Figure 9(a), 9(b), 9(c), 9(d), 9(e).

Based on the polynomial regression analysis conducted between soil physical and chemical properties and total carbon stock, the coefficient of determination (R^2) values were found to vary considerably. Soil organic carbon (C-Organic) explained 88% of the variation in total carbon stock and had a positive relationship with total carbon stock, while soil bulk density explained 66.21% of the variation and had a negative relationship with total carbon stock. Cation exchange capacity (CEC) explained 25.66% of the variation and showed a positive relationship, soil pH H_2O explained 14%, and pH NaF explained 11% of the variation in total carbon stock, both showing positive relationships. In terms of soil texture, the silt fraction explained 72% of the variation and showed a positive relationship, whereas the clay fraction explained 33% and the sand fraction explained 59% of the variation in total carbon stock, both showing negative relationships.

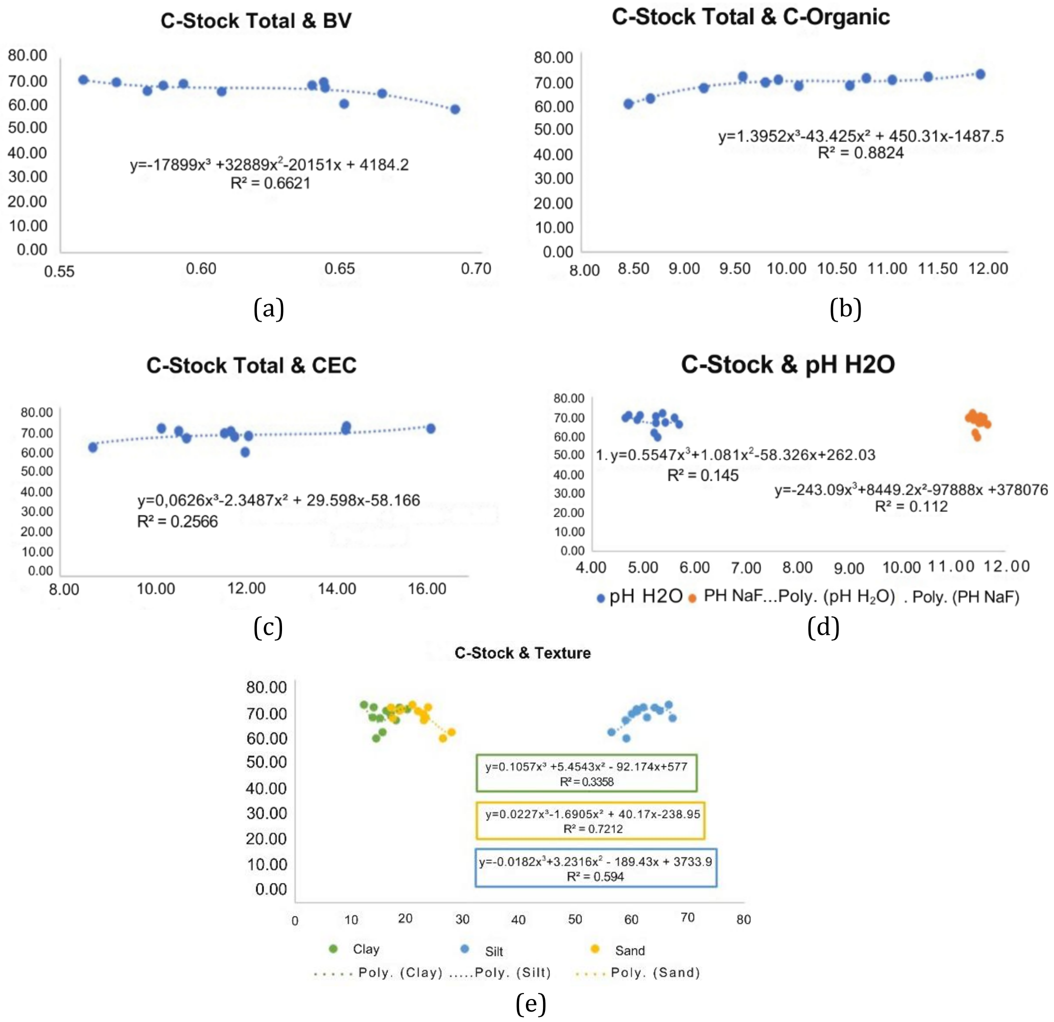

Fig. 9. Polynomial regression analysis between (a) soil organic carbon (C-Organic) and total carbon stock; (b) bulk density (BD) and total carbon stock; (c) cation exchange capacity (CEC) and total carbon stock; (d) soil pH and total carbon stock (e) soil texture and total carbon stock

Other soil physical and chemical properties such as CEC, soil pH H_2O and pH NaF, as well as soil texture, showed indirect influences on carbon stock. High CEC values indicate the abundance of cations stored and exchanged in the soil by organic matter (Sahfitra, 2023), while soil pH H_2O and pH NaF had a positive influence on carbon stock but with relatively low effects. Soil pH has a positive relationship with carbon stock since neutral to slightly alkaline pH supports nutrient availability for plants, thereby optimizing photosynthesis, which in turn increases biomass and influences carbon stock. Furthermore, soils with a higher silt fraction showed the strongest positive influence compared to other fractions (Uthbah et al., 2017), as higher silt content tends to provide meso and micropores that optimize organic matter decomposition. In contrast, high clay content reduces porosity and hinders decomposition, while excessive sand content prevents the soil from retaining water and air effectively, which also disrupts the decomposition process of organic matter.

4. Conclusions

The results of the study indicate that the total carbon stock value of tea plants in the Pemandangan Block, UP Tambi, tends to increase with plant age. The total carbon stock was recorded at 63.17 tons/ha in 10-year-old plants, 67.26 tons/ha in 30-year-old plants, 67.87 tons/ha in 40-year-old plants, and reached 69.40 tons/ha in 100-year-old plants. This finding demonstrates that older tea plants contribute more significantly to carbon storage through both biomass and soil, highlighting the substantial potential of tea plantations in supporting climate change mitigation efforts.

Furthermore, soil properties were found to play an important role in influencing carbon stock in both soil and biomass. The most dominant factor was soil organic carbon content, followed by soil texture and bulk density. High levels of soil organic carbon enhanced soil carbon storage, while soil texture determined the capacity for retention and decomposition of organic matter. Conversely, bulk density showed a negative relationship, as denser soils provide less space for roots and microorganisms to support carbon accumulation. Therefore, the management of tea plantations that considers soil physical and chemical properties will contribute to optimizing carbon stock enhancement.

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