VARIABILITY OF ORGANIC CARBON CONTENTS IN TEA SOILS OF CHATTOGRAM VALLEY

S. Das[1*] and A. Biswas[1]

[1]Soil Science Division, Bangladesh Tea Research Institute, Srimangal 3210, Moulvibazar

** Corresponding author's e-mail: shuvadas388@gmail.com*

Abstract

Soil organic carbon (SOC) plays a pivotal role in maintaining soil fertility, agricultural productivity, and the long-term sustainability of cropping systems, including perennial plantations like tea gardens. This study investigates the spatial and vertical distribution of SOC in the soils of 14 tea estates situated in the Chattogram Valley, a key tea-producing region of Bangladesh. A total of 507 soil samples were collected across three distinct depth intervals: 0–23 cm, 23–46 cm, and 46–92 cm. The average SOC content across these layers was found to be 0.82%, 0.66%, and 0.55%, respectively which are consistently below the national optimal threshold of 1.0% SOC for agricultural soils. The results reveal a significant decline in SOC with increasing soil depths, while strong positive correlations were observed between surface and subsurface SOC levels. These trends underscore the ongoing depletion of organic carbon in tea-growing soils, likely due to prolonged monoculture practices and insufficient organic matter input. The study highlights the urgent need for region-specific soil management strategies aimed at enhancing SOC levels, such as the incorporation of organic amendments, cover cropping, and reduced tillage. Strengthening SOC not only improves soil fertility and tea yield potential but also contributes to broader environmental goals like carbon sequestration and climate resilience. The findings offer crucial insights for sustainable land management practices in tea plantations across the Chattogram Valley and similar agro-ecological zones.

Keywords: Tea estates, Carbon sequestration, Tea productivity, Soil management

1. Introduction

Soil organic carbon (SOC) plays a central role in the global carbon cycling and has become a key focus for mitigating negative effects of climate change. Recent studies emphasize the importance of SOC sequestration as a method for offsetting greenhouse gas emissions and improving soil health. Research shows that SOC in soils serves not only as a major terrestrial carbon sink but also as a crucial factor in enhancing soil fertility and agricultural productivity (Goldstein *et al.,* 2020). In particular, the role of SOC in enhancing soil resilience to climate change has gained significant attention in recent years, with studies showing that soils with higher organic carbon content are more resilient to drought, erosion, and nutrient loss (Smith *et al.,* 2022). The link between SOC sequestration and climate resilience has been well established in recent studies. For instance, a study by Jones *et al.* (2021) demonstrated that soils with higher SOC stocks are more likely to retain moisture during drought periods, which is critical for maintaining crop productivity in changing climate conditions. Furthermore, SOC sequestration has been proposed as a natural climate solution to mitigate the impacts of climate change by reducing atmospheric CO_2 concentrations (Manning *et al.,* 2023).

These findings underscore the importance of understanding SOC dynamics, particularly in agricultural systems like tea cultivation, where soil management practices directly influence SOC levels and, consequently, carbon sequestration potential. Soil carbon storage and its management are heavily influenced by land use, soil type, and environmental conditions. Research in tropical regions has shown that deforestation, agricultural activities, and soil management practices significantly alter SOC pools, contributing to climate change (Jobbagy and Jackson, 2022). However, recent studies have expanded on these earlier findings by focusing on the effects of more specific land management practices, such as organic farming, conservation tillage, and agroforestry, which can enhance SOC sequestration (Wiesmeier *et al.,* 2024). In the context of tea estates, where organic matter inputs from plant residues and microbial activity are substantial, soil carbon content is expected to be higher in the surface soil layers compared to deeper layers. This is consistent with the findings of Akter *et al.* (2024) and Wang *et al.* (2019), who reported that soil management practices in tea plantations have a direct impact on SOC content, influencing both soil fertility and its ability to sequester carbon. The sustainability of tea cultivation depends not only on maintaining optimal soil health but also on ensuring that SOC levels are managed in a way that maximizes carbon sequestration. At present, in Bangladesh, 168 tea estates, total grant area of 115392 ha where tea is cultivated in 53.4% of total area. This research is focused on investigating the organic carbon (OC) status of tea soil of 14 tea estates of Chattogram region. where about 50% of total area of Chattogram valley is using for tea cultivation.

2. Materials and Methods

A total of 507 composite soil samples were collected at three soil depths (0-23 cm, 23-46 cm, and 46-92 cm) across 14 tea estates in south eastern part of Chattogram region, Bangladesh located between 22.13^0N -22.97^0 N latitude and 91.96^0 E – 91.65^0 E longitude (Fig.1). the selected Tea Estates were: (1) A. Manik, (2) Barmasia, (3) BTRI Expt Station, (4) BTRI Sub-station, (5) Ellahinoor, (6) Halda Vally, (7) New Danmara, (8) Oodaleah, (9) Rangapani, (10) Neptune, (11) Trintohori, (12) Danmara, (13) Ramgarh, and (14) Naseha. The wet oxidation method (Walkley and Black, 1934) was employed for SOC determination. Soil samples were air-dried and sieved through a 2 mm sieve before analysis. The samples were then subjected to Walkley and Black's wet oxidation process, with the absorbance of the resulting solution measured at 600 nm using a UV-VIS spectrophotometer.

2.1 Statistical analysis

Statistical analysis was carried out by MS Excel and SPSS software 16 (SPSS Inc., Chicago, IL). A heatmap of correlation coefficients and a linear regression model were generated by using Python in Google Colab, utilizing libraries such as pandas, seaborn, scikit learn, and matplotlib. To assess the variability in %OC across different soil depths and tea estates, an analysis of variance (ANOVA) was performed to determine whether significant differences exist between soil depths (0-23 cm, 23-46 cm, 46-92 cm) and locations. Pearson's correlation coefficients (r) were calculated to evaluate the strength and direction of the linear relationships between SOC content at different soil depths. The strength of the correlation was interpreted based on the following scale: very weak ($r < 0.2$), weak ($0.2 < r < 0.4$), moderate ($0.4 < r < 0.6$), strong ($0.6 < r < 0.8$), and very strong ($r > 0.8$).

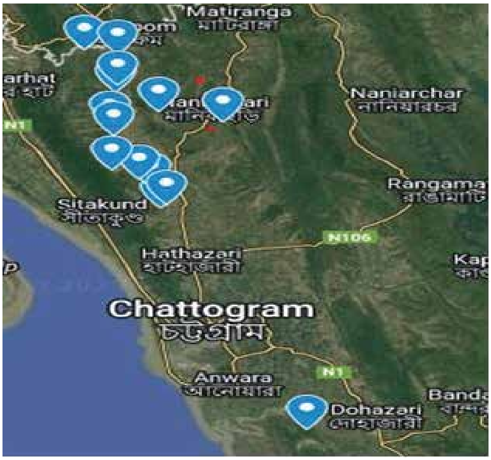

Fig. 1 Soil sampling sites in the google map

A positive correlation between the surface and deeper layers indicates that surface processes, such as root biomass decomposition and microbial activity, have a lasting influence on SOC in the subsurface layers. Regression models were developed to quantify the relationships between percent SOC at different depths. Linear regression models were fitted for the relationships between SOC content at 0–23 cm and both 23–46 cm and 46–92 cm depths. These models were evaluated for goodness of fit using R-squared (R^2) values and confidence intervals. The regression analysis provides a deeper understanding of how SOC dynamics at the surface influence subsurface layers and may be used to predict SOC content in deeper layers based on surface measurements. The Pearson correlation coefficients (r) were interpreted to examine the nature of relationships between SOC at different depths. A strong positive correlation between 0–23 cm and 23–46 cm ($r = 0.74$) suggests that the SOC content in the surface soil influences the SOC content in the subsurface layers. This relationship is significant for soil fertility management, as changes in surface SOC can be indicative of potential changes in deeper soil layers. Similarly, moderate to weak correlations observed between 23–46 cm and 46–92 cm ($r = 0.65$ and $r = 0.46$, respectively) highlight that while surface processes continue to affect deeper layers, other factors such as leaching, microbial decomposition, and land management practices may also play a role in the distribution of SOC at greater depths.

3. Results and Discussions

The results shown in the Fig. 2, represent the %SOC distribution across three soil depths (0–23 cm, 23–46 cm, and 46–92 cm) at various sampling locations. The mean of %SOC represented by the bars for each depth showing the %SOC is highest in the surface layer (0–23 cm) and decreased with depth. This trend highlights the accumulation of organic matter in the upper layers due to the decomposition of plant residues and microbial activity, which is typical in long-term tea cultivation (Wang, *et al.,* 2019; Akter, *et al.,* 2024). Relatively higher % SOC was founded in the surface layers of Andhar Manik T.E., BTRI Sub-Station, New Dantmara T.E., Tintohori T.E. and Naseha T.E., meanwhile in Baramasia T.E., Elahinoor T.E. and Halda Valley T.E. are showing the lower overall %SOC levels.

The amount of carbon in the top 30 cm of soil is mainly affected by variations in rainfall, vegetation cover, and soil type while subsurface soil carbon is influenced by land use and soil characteristics.

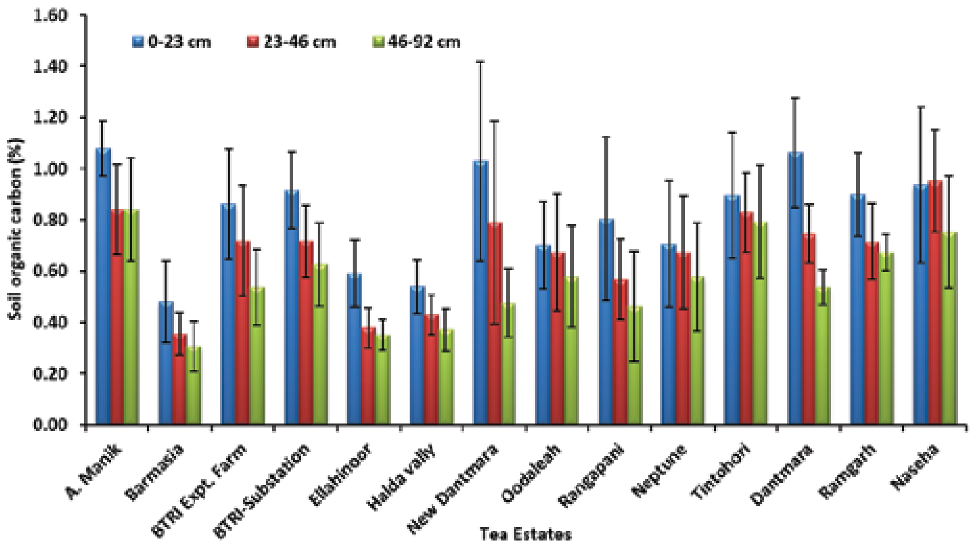

Fig. 2 Variation in SOC at three soil depths across different tea estates of Chattogram region (Letter a-d, α-δ and p-r dentoe the SOC concentration at soil depths of 0-23 cm, 23-46 cm and 46-92 cm, respectively).

The statistical differences between depths and in different locations are denoted by the letters above the bars. There are significant ($p<0.05$) differences in OC (%) distribution among the three depths of soils in the tea estates of the Chattogram region. Roy *et al.* (2024) stated that the mean concentrations of organic matter (OM), was found higher in top soil rather than subsurface soil depth with significant ($p< 0.05$) difference in the tea estates of Chattogram regions.

Table 1. ANOVA with descriptive values of %SOC at three different depths across the sites

Depth	Minimum	Maximum	Mean	F
0-23 cm	0.25	2.07	0.82	9.194***
23-46 cm	0.23	1.84	0.66	10.278***
46-92 cm	0.16	1.22	0.55	12.171***

*** Significant at p<0.001

From the Table 1, the minimum and maximum value of %SOC was observed 0.25% to 2.07%, 0.23% to 1.84% and 0.16% to 1.22% in the 0-23cm, 23-46cm and 46-92cm depth of soil respectively. Additionally, average value of SOC was found 0.82%, 0.66% and 0.55% at three different depths of soil respectively. The F values are indicating that the relationship between soil depth and %SOC varied significantly ($p<0.001$) and %SOC significantly decreases with the depth (Gaudinski *et al.,* 2000). It has been reported that changes of land-uses and tea plantations increased organic matter input into soils via leaf and root residues, altering soil microbial activity as well as fertilization practice which significantly improved the SOC in upper layer of soil (Shu *et al.,* 2025).

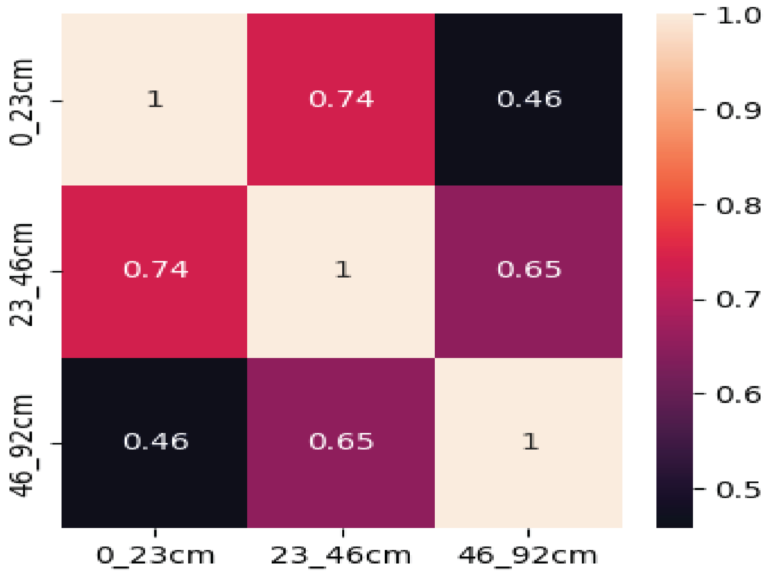

Fig. 3 Correlation matrix for % SOC among the three depths of soil

The heat map in Fig. 3 illustrates the Pearson correlation coefficients between SOC (%) at different soil depths. A strong correlation (r = 0.74) was observed in SOC (%) between first two depth, indicating that SOC content in topsoil significantly influences the subsurface layer. Similarly, a moderate correlation (r = 0.65) in SOC between the 23–46 cm and 46–92 cm was observed, suggesting some level of OC persistence though its influence reduced with increasing depths.

Furthermore, the correlation between 0–23 cm and 46–92 cm is (r = 0.46) the lowest one, suggesting the SOC (%) in deeper layer is less impacted by surface processes and highly influenced by prolonged decomposition, leaching, stabilization processes, and land management practices (Novara et al., 2015). In practical terms, these correlations suggest that improving SOC in the surface soil can have a long-term positive impact on subsurface SOC levels. This finding is crucial for soil management practices aimed at enhancing both soil fertility and carbon sequestration in the tea estates.

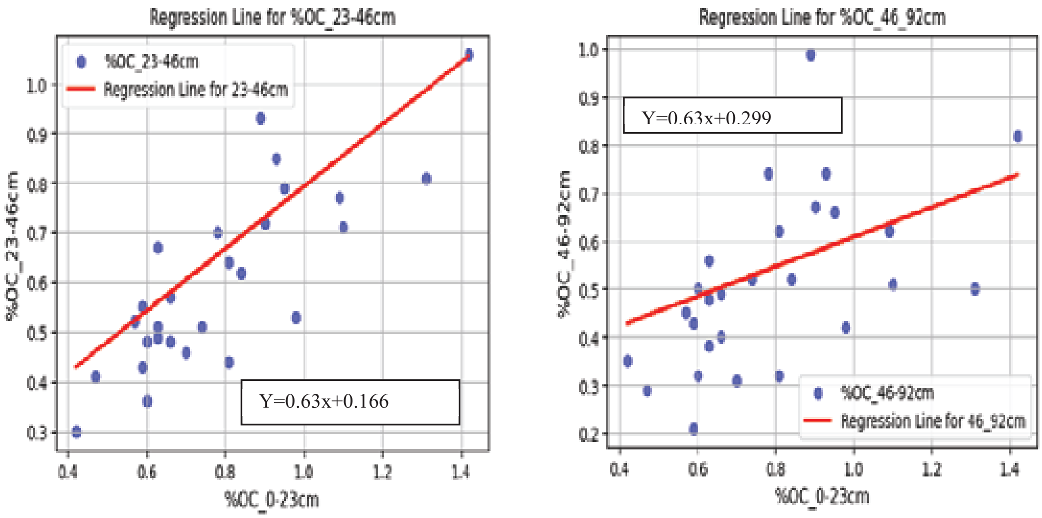

Fig. 4 Regression of SOC contents among different soil depths

The regression analysis in Fig. 4 depicts a strong positive correlation between percent SOC at three depths: 0–23 cm on x-axis and 23–46 cm on y-axis and again 0–23 cm on x-axis and 46-92 cm on y-axis. Individual data points which were shown on scatter plot clustering around the regression line suggest a well-defined linear relationship, although some variations are observed. The uncertainty in the model's prediction is estimated by the surrounding confidence interval with the regression line and the value of R^2= 0.37 which indicates a moderate linear relationship and also explains 37.54% variability in the deeper organic C based on the surface SOC content. This relationship between the depths suggests that organic carbon dynamics in the top soil markedly influence the deeper soil layer, which is important for realizing SOC sequestration and soil fertility management. In deeper soil layers soil organic carbon accumulation affected by surface processes such as microbial activity, root biomass decomposition, soil properties and transit time. Prolonged research on SOC dynamics, particularly in deep layers of soil is crucial for improving biogeochemical and climatic models by analyzing microbial activity, SOC fractions and greenhouse gas emissions (Sulman *et al.,* 2018).

The observed variations in SOC content across the different tea estates of Chattogram can be attributed to several factors, including soil texture, management practices, land level and climatic conditions. Estates with higher SOC levels tend to have better soil management practices, such as regular addition of organic matter, proper irrigation systems, and minimal disturbance to the soil. These practices promote microbial activity, which enhances organic carbon sequestration and stabilizes it in the soil. Furthermore, the type of tea plantation system (e.g., organic vs. conventional) can significantly influence SOC accumulation. Estates that follow organic farming practices generally show higher SOC content due to increased use of compost and organic fertilizers. Soil texture is another critical factor influencing SOC dynamics. Soils with higher clay content tend to retain more organic matter compared to sandy soils, as the smaller particle size increases the soil's ability to bind organic carbon (Jobbagy and Jackson, 2000). Tea estates with soils rich in clay minerals generally exhibit higher SOC content.

Rainfall patterns also play a significant role in SOC distribution. Estates located in areas with higher annual precipitation tend to have higher SOC levels, as more rainfall promotes the decomposition of plant residues and supports the growth of vegetation that contributes organic matter to the soil. Conversely, estates in drier areas may have lower SOC content due to reduced plant growth and slower decomposition rates.

4. Conclusions

This study reveals a clear vertical decline and overall deficiency of soil organic carbon (SOC) in the tea-growing soils of the Chattogram Valley, with SOC levels falling below the national optimal threshold across all sampled depths. These findings underscore the need for region-specific, sustainable soil management practices particularly those that prioritize organic matter inputs for improving soil fertility, enhancing carbon sequestration, and sustaining long-term productivity in tea plantations. While the study provides valuable baseline data, it is limited by its reliance on one-time sampling, which restricts understanding of temporal variations and long-term trends. Future research should incorporate longitudinal sampling and monitoring across different seasons and years to better capture SOC dynamics. Such studies will be crucial for developing more precise, adaptive management strategies tailored to varying soil types, land use histories, and climatic conditions in the Chattogram Valley.

Conflicts of Interest

The authors declare no conflicts of interest regarding publication of this paper.

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