



Research Article

Carbon Stock Assessment in *Sonneratia apetala* Afforested Mangroves: A Case Study from Cox's Bazar, Bangladesh

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Abstract

Sonneratia apetala is a key species for mangrove afforestation projects in Bangladesh and plays a crucial role in ecosystem restoration and carbon sequestration. The research on how the total carbon stock (TCS) varies across *S. apetala* plantations in Cox's Bazar remains limited. Thus, in this study, the biomass and soil carbon stock were quantified across nine *S. apetala* afforested sites in Cox's Bazar to assess spatial variation and influencing factors. The total biomass carbon (TBC) was calculated by summing the aboveground (AGBC) and belowground (BGBC) biomass carbon, while the soil organic carbon stock (SOCS) was determined from the 0–40 cm soil depth. Descriptive statistics, ANOVA, Pearson correlation, and multiple linear regression (MLR) were used to analyze spatial differences and identify key predictors of carbon stocks. The results revealed notable variation in tree and soil parameters across the sites. Although tree height and diameter at breast height (DBH) varied among the sites, the variation was not statistically significant ($p > 0.05$). In contrast, the SOC content and bulk density (BD) significantly differed ($p < 0.001$), whereas the pH, salinity, and total nitrogen (ToN) content remained statistically similar ($p > 0.05$). The SOCS ranged from 13.04 ± 6.17 to 17.42 ± 5.18 t ha⁻¹, whereas the TBC ranged from 28.26 ± 26.34 to 53.82 ± 45.36 t ha⁻¹. The MLR results revealed that BD was a significant predictor of SOCS ($p < 0.05$) at most of the sites. Despite variations in TBC and SOCS, TCS did not vary significantly ($p > 0.05$), with TBC contributing 63.8% to 79.4% of the total stock. Correlation analysis indicated that TCS was influenced mainly by tree height, DBH, and soil nutrients, whereas salinity and pH had minimal effects. These insights may support improved mangrove management in climate change mitigation and adaptation strategies.

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Introduction

Greenhouse gas-induced climate change is among the most pressing environmental concerns of the 21st century (Abbass et al., 2022). Among these gases, carbon dioxide (CO₂) is the most significant contributor to global warming, leading to adverse impacts such as

rising global temperatures, extreme weather events, and sea-level rise (Jiao, 2023). In response to these challenges, carbon sequestration has emerged as a crucial natural process for mitigating climate change through the absorption and storage of CO₂ from the atmosphere (Bose et al., 2024; Dang et al., 2019; Singh

et al., 2023). This process is facilitated by various terrestrial, aquatic, and coastal ecosystems. Among them, mangrove forests are recognized as among the most carbon-rich coastal ecosystems because they can play a crucial role in carbon sequestration (Ismail et al., 2025). They are highly productive and unique ecosystems that act as powerful carbon sinks, efficiently storing 3 to 5 times more carbon than terrestrial forest ecosystems do (Ahmed et al., 2022; Harishma et al., 2020; Hong et al., 2017). Despite occupying a small portion, comprising less than 1% of the total coastal ocean area worldwide, mangrove forests contribute more than 15% (24 TgCyr⁻¹) of global carbon accumulation (Alongi, 2014). Additionally, mangroves provide diverse ecosystem services, increasing community resilience and sustainability through disaster mitigation and livelihood support.

Despite their immense significance, mangroves are among the most threatened ecosystems. Human activities such as industrialization, urbanization, and farming have caused severe damage to these areas (Wang et al., 2021). In response, afforestation and reforestation are now considered nature-based solutions (Ahmed et al., 2022). These efforts help vulnerable mangrove regions adapt to global warming by capturing atmospheric carbon (Uddin et al., 2022). Thus, many countries worldwide have initiated mangrove plantation programs to restore degraded mangrove regions. Since the 1960s, the Government of Bangladesh has successfully afforested approximately 280 km² of land with mangrove plantations to safeguard against natural disasters, stabilize the land, and provide livelihood support to the local community (Ahmed et al., 2022; Barua et al., 2020; Uddin et al., 2022). Initially, mangrove plantations in the coastal areas of Bangladesh struggled because of a lack of knowledge on proper plantation techniques (Islam et al., 2015). Among the planted species, *Sonneratia apetala* (Keora) was the most successful along the entire coastal belt, followed by *Avicennia officinalis* (Baen) in the eastern coastal belt of Bangladesh (Islam et al., 2015a; b). Large-scale afforestation with *S. apetala* was carried out under more than 16 development projects, covering 0.192 million hectares of accreted land by 2013 (Islam et al., 2016). Over time, *S. apetala* has become the preferred species because of its superior survival and growth rate in newly accreted lands (Islam et al., 2015b). Other species, such as *Heritiera fomes* (Sundri), *Excoecaria agallocha* (Gewa), *Xylocarpus moluccensis* (Passur), *Aegiceras corniculatum* (Khalshi), and *Nypa fruticans* (Golpata), have also been shown to be suitable for experimental trials within *S. apetala* plantations.

S. apetala, the largest and tallest mangrove tree in both natural and afforested mangrove forests in Bangladesh, can reach up to 20 meters in height and 80 cm in diameter (Islam et al., 2016). Its substantial carbon sequestration potential is attributed to the aboveground

biomass (stem, branch, bark, and leaves), belowground biomass (roots), and underlying soil. Accurately quantifying the carbon stock in these components is essential for understanding its role in carbon storage and for informing afforestation initiatives (Ahmed et al., 2024a). Allometric models, which estimate biomass using tree-specific parameters such as diameter at breast height (DBH), tree height, and wood density, are widely used for this purpose (Chave et al., 2005; Kusmana et al., 2018; Rahman et al., 2021; Zhu et al., 2021). These models are typically derived from destructive sampling but, once developed, provide a reliable and nondestructive method for estimating biomass and carbon stocks at the tree and stand levels. In mangrove ecosystems dominated by *S. apetala*, species-specific allometric equations are particularly important because of the variability in growth patterns, wood density, and site conditions (Ismail et al., 2025). Despite this importance, a gap remains in research specifically addressing the carbon stock estimation of *S. apetala* in afforested mangrove ecosystems of Cox's Bazar, Bangladesh.

Thus, this study aims to estimate the total carbon stock (TCS) of *S. apetala* in afforested mangrove ecosystems across various locations in Cox's Bazar, Bangladesh. The specific objectives of the study are (1) to quantify the total biomass carbon stock (TBC) by integrating both aboveground and belowground biomass components; (2) to assess the spatial variation in TBC and soil organic carbon stock (SOCS) across afforested sites using analysis of variance (ANOVA); (3) to examine the influence of key biophysical and environmental factors, such as tree height, DBH, salinity, pH, bulk density (BD), total nitrogen (ToN), and soil organic carbon (SOC), on carbon storage; and (4) to develop and evaluate regression models for predicting SOCS based on relevant soil parameters. The findings of this study may provide valuable insights into the carbon stock dynamics of afforested *S. apetala* mangroves and enable data-driven strategies for climate-resilient coastal ecosystem management.

Materials and methods

1) Study area

This study was conducted in afforested mangrove areas of Cox's Bazar District, which is located on the southeastern coast of Bangladesh. Cox's Bazar lies between 20°43' and 21°56' north latitude and 91°50' and 92°23' east longitude (Figure 1). The area has a tropical monsoon climate with high temperatures, heavy rainfall, and high humidity. The mean annual temperature ranges from 16.1°C to 34.8°C, with an average rainfall of 4285 mm (Roy et al., 2023). The coastal landscape of Cox's Bazar comprises fluvial and tidal deposits formed by weathering processes from surrounding terrains, including steep cliffs and mountainous areas. These materials are carried by major

rivers such as the Matamuhuri, Baghkhali, and Rezu Khal, along with numerous smaller tributaries and canals, contributing to the formation of newly accreted coastal landforms, locally known as 'Char'. This unique landscape has facilitated the development of mangrove afforestation projects. The Bangladesh Forest Department (BFD) started an afforestation program in the coastal areas of Bangladesh in 1960–61 (Islam et al. 2015b). Since then, various government departments and nongovernmental organizations, as well as local, national, and international organizations in cooperation with local stakeholders, have successfully implemented several afforestation and reforestation projects on the coast of Cox's Bazar District (Hossain et al., 2001). These projects have focused primarily on areas such as Chakaria Sundarban (CS), Teknaf Peninsula (TP), Sonadia Island (SI), Banks of Moheshkhali Channel (MoC), Matamuhuri Channel (MC), Naf River (NR), Saplapur Union (SU), Badarkhali Union (BU), Shah-Porir Dip (SPD), and Nuniar Chara (NC) mangrove forest. These regions play crucial roles in carbon sequestration and act as natural barriers against storm surges and rising sea levels.

2) On-site sampling and measurements

The field survey was conducted between October 2024 and January 2025. A total of 18 representative plots (15 m × 15 m) were selected using a stratified random sampling design (SRSD), with an equal number of plots allocated to each of the nine afforested areas. All plots were selected from *S. apetala* afforested sites that were planted after 2000. The plots were chosen on the basis of similar characteristics, including slope, aspect, altitude, and soil type. Tree growth parameters such as height and DBH were measured at each site. Tree height was measured using a Nikon Forestry Pro II Laser Rangefinder/Hypsometer, while DBH was recorded using a diameter tape. For every tree, a corresponding soil sample was collected from a depth of 0–40 cm to assess soil quality indicators, including pH, salinity, BD, ToN, and SOC. Each soil core collected from the 0–40 cm depth was homogenized to form a composite sample representing the entire soil layer, and no depthwise slicing was performed. The selected depth (0–40 cm) represents surface soil carbon and reflects practices commonly adopted in mangrove carbon studies in Bangladesh (Ahmed et al., 2024b; Ismail et al., 2025; Miah and Hossain, 2021; Ray et al., 2011), where deep coring is logistically constrained. Therefore, the SOCS estimates in this study may not represent full ecosystem blue carbon stocks.

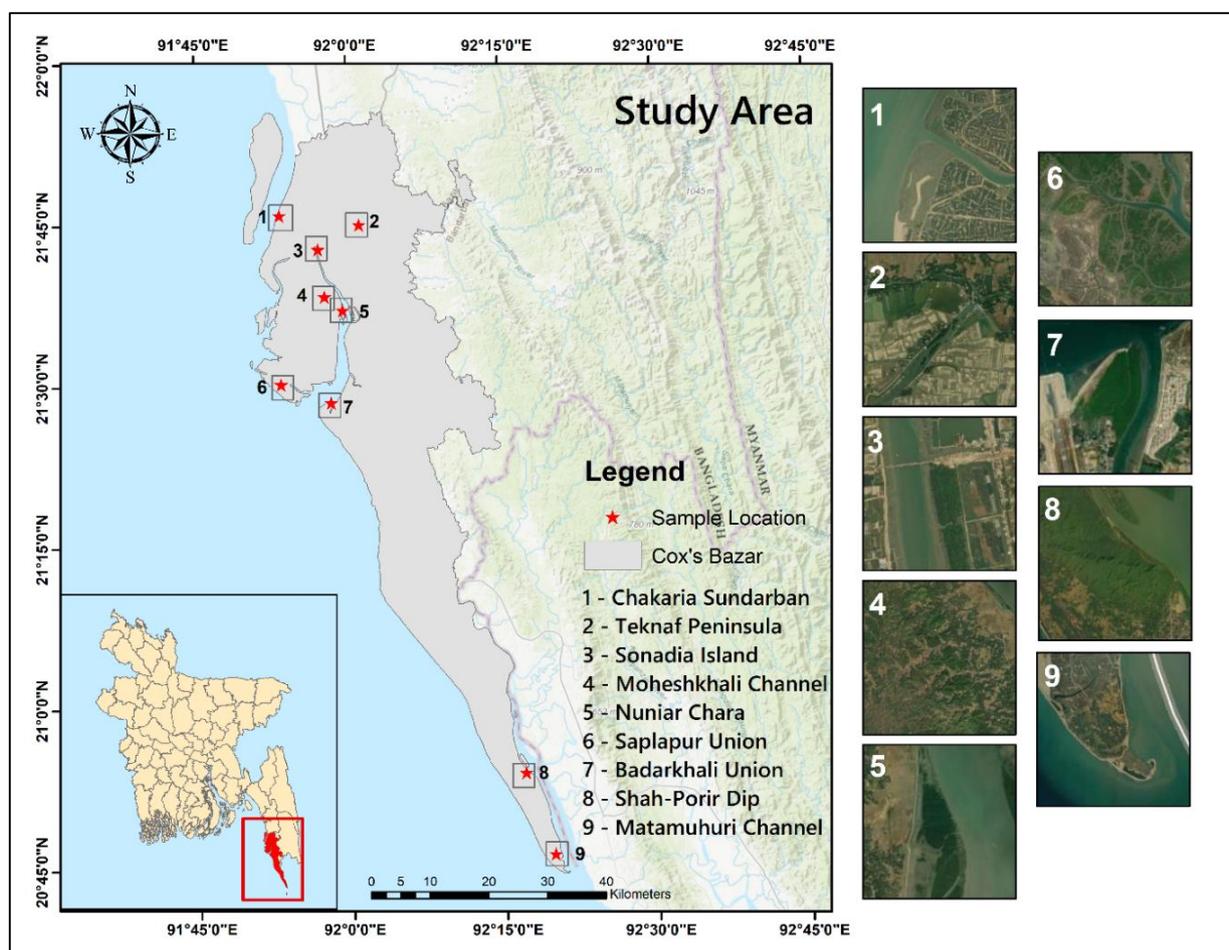


Figure 1 Map of the study area.

3) Determination of soil physiochemical parameters

Soil pH and electrical conductivity (EC1.5, dS m⁻¹) were measured using a multiparameter water analyzer (Model: HI98194, Hanna Instruments), with soil extracted using distilled water at soil-to-water ratios of 1:3 and 1:5, respectively. A conversion factor of 0.64 was subsequently applied to the EC1.5 values to calculate the soil salinity in parts per thousand (ppt) (Slinger and Tenison, 2007). ToN content was measured using the Kjeldahl method, which involves wet digestion followed by distillation to quantify ammonium (Ahmed et al., 2024a). The SOC content was determined using the Walkley–Black method, in which organic matter is oxidized with potassium dichromate in an acidic medium (Walkley and Black, 1934). Bulk density (BD, g cm⁻³), which represents the mass of dry soil per unit volume, was measured using the core method (Al-Shammary et al., 2018). A stainless steel cutting ring with a diameter and height of 5.0 cm was used as the soil sampler. The volume of the ring was calculated using the formula $V = \pi r^2 h$, where r is the radius and h is the height. Moist soil samples were collected, weighed according to the sample volume, and then oven-dried at 105°C for 24 hours. BD was calculated by dividing the oven-dried soil weight by the soil volume according to Eq. 1. Finally, the SOCS was calculated to quantify the amount of carbon stored in the soil per unit area. For each i th soil layer, SOCS was estimated using Eq. 2.

$$\text{Bulk density} = \text{Dry soil weight (g)} / \text{Soil volume (cm}^3\text{)} \quad (\text{Eq. 1})$$

$$\text{SOCS}_i = \text{SOC}_i \times \text{BD}_i \times D_i \times 0.1 \quad (\text{Eq.2})$$

where SOC_i is the soil organic carbon content (%), BD_i is the bulk density (g cm⁻³), and D_i is the thickness (cm) of the i th layer. The factor 0.1 is a unit conversion constant to express the results in tons per hectare (t ha⁻¹).

4) Estimation of total biomass carbon (TBC)

Allometric Eqs. 3–7, developed by Ren et al. (2010), were used to estimate the aboveground (stem, branch, bark, and leaf) and belowground (root) biomass of the *S. apetala* plantations. Biomass carbon was then calculated by multiplying the biomass of each component by its respective average carbon concentration: 46.8% for stems, 43.7% for branches, 42.8% for bark, 38.4% for leaves, and 43.3% for roots (Ren et al., 2010). Finally, the TBC for each individual tree was determined by summing the carbon stored in all components of the tree as per Eq. 8.

$$\text{AGB}_{\text{stem}} = 0.061(D^2H)^{0.821}, R^2 = 0.997 \quad (\text{Eq.3})$$

$$\text{AGB}_{\text{branch}} = 0.205(D^2H)^{0.572}, R^2 = 0.989 \quad (\text{Eq.4})$$

$$\text{AGB}_{\text{bark}} = 0.038(D^2H)^{0.564}, R^2 = 0.963 \quad (\text{Eq.5})$$

$$\text{AGB}_{\text{leaf}} = 0.056(D^2H)^{0.536}, R^2 = 0.913 \quad (\text{Eq.6})$$

$$\text{BGB}_{\text{root}} = 0.038(D^2H)^{0.759}, R^2 = 0.991 \quad (\text{Eq.7})$$

$$\text{TBC}_i = \sum \text{AGBC}_i + \sum \text{BGBC}_i \quad (\text{Eq.8})$$

Where AGB_{stem} is the stem biomass (kg), $\text{AGB}_{\text{branch}}$ is the branch biomass (kg), AGB_{bark} is the bark biomass (kg), AGB_{leaf} is the leaf biomass (kg), BGB_{root} is the root biomass (kg), D is the diameter at breast height (cm), and H is the height (m). AGBC_i is the aboveground biomass carbon, BGBC_i is the belowground biomass carbon, and TBC_i is the total biomass carbon of the i th tree.

5) Statistical analyses

All the statistical analyses were conducted using the R programming environment (version 4.4.2). Descriptive statistics, including the mean and standard deviation, were calculated for each variable by location and summarized in mean \pm SD format. One-way analysis of variance (ANOVA) was performed to assess the significance of differences in three biophysical attributes (e.g., height and DBH), soil properties (e.g., pH, salinity, BD, SOC, and ToN), tree density, SOCS, TBC, and TCS across different afforested sites. To evaluate the relationships between SOCS and the explanatory variables, linear regression analyses were conducted separately for each location. Specifically, multiple linear regression (MLR) was applied to model SOCS as a function of pH, BD, salinity, and ToN. Model performance was assessed using the coefficient of determination (R^2). Additionally, scatter plots of observed versus predicted values were generated for each location to visually assess model accuracy, with the corresponding correlation coefficients annotated on each plot.

Results and discussion

1) Tree-specific and soil physiochemical parameters

Table 1 and Figure 2 show the summary statistics and ANOVA-based comparisons of tree structural and soil physiochemical parameters across the *S. apetala* afforested sites along Cox's Bazar Coast of Bangladesh. The tallest tree height occurred on the TP (14.88 \pm 5.28 m), followed closely by that on the MC (14.32 \pm 4.92 m), whereas the shortest height occurred on the SU (11.99 \pm 5.47 m), indicating a 24.1% difference. DBH was highest for TP (19.10 \pm 8.95 cm) and lowest for SU (14.20 \pm 7.55 cm), representing a 34.5% increase. Moderate DBH values were recorded for MC (18.43 \pm 7.99 cm), BU (17.61 \pm 10.15 cm), and NC (16.39 \pm 8.17 cm). However, ANOVA revealed no significant differences in height ($p > 0.05$; Figure 2a) or DBH ($p > 0.05$; Figure 2b), suggesting that tree structural parameters did not

vary significantly across the sites despite the observed variation.

The salinity levels across the sites were moderately uniform, ranging from 3.49 ± 0.70 ppt in the MoC to 3.97 ± 1.31 ppt in the SI, indicating a difference of 13.8%. The soil pH also slightly varied, with values ranging from 6.06 ± 0.86 in the MC to 6.78 ± 0.96 in the MoC. Neither parameter differed significantly across the sites (salinity: $p > 0.05$; Figure 2c; pH: $p > 0.05$; Figure 2d), indicating a relatively homogeneous saline environment. Similarly, ToN values ranged from $0.41 \pm 0.24\%$ in SU to $0.55 \pm 0.31\%$ in MC and TP, with no significant difference ($p > 0.05$; Figure 2e), indicating that the nitrogen content was comparable across the plantations. However, the soil BD varied highly significantly among the sites ($p < 0.001$; Figure 2f). The lowest BD was recorded in the TP (0.78 ± 0.07 g cm⁻³), and the highest was recorded in the CS (0.94 ± 0.07 g cm⁻³), indicating a 20.5% increase, with visibly tighter boxplots for CS, BU, and SU indicating less variation within those sites. SOC also showed significant spatial variability ($p < 0.001$; Figure 2g), with values ranging from $3.52 \pm 1.77\%$ in the CS to $5.73 \pm 1.95\%$ in the TP, representing a notable increase of 62.8%. Higher SOC values were also observed in BU, SPD, and MoC, whereas relatively lower concentrations were reported in CS and SI. These findings highlight considerable site-to-site variation in soil fertility and organic matter status across the *S. apetala* plantations.

2) Community structure and characteristics

To assess the community structure and characteristics of *S. apetala* plantations, tree density and the allometric relationship between DBH and tree height were analyzed across different afforestation sites. The mean tree density varied across the sites, ranging from 488.89 trees ha⁻¹ on the TP to 933.33 trees ha⁻¹ on the CS (Figure 3). The highest mean density in the CS stands suggests a relatively dense stand structure, whereas the mean densities of the TP and SPD stand structures were relatively lower. Despite these differences, a one-way ANOVA indicated no statistically significant variation in tree density among the sites ($p > 0.05$). These results suggest moderate uniformity in plantation efforts across sites, although slight spatial differences may arise because of local site conditions, management practices, or initial planting success. Additionally, the relationships between the DBH and tree height were strongly linear across all the afforestation sites (Figure 4). The coefficients of determination (R^2) ranged from 0.73 for SPD to 0.86 for BU, indicating a consistently high degree of predictability in height based on the DBH across the sites. All the relationships were statis-

tically significant ($p < 0.001$) at the 95% confidence intervals. The strong and consistent DBH–height relationships across the sites suggest that *S. apetala* maintains a stable allometric growth pattern, demonstrating its adaptability and structural consistency under dynamic environmental conditions within afforested regions.

3) Assessment of carbon stock

3.1) Componentwise biomass carbon stock

The biomass carbon stock of different plant components, such as stems, branches, bark, leaves, and roots, varied notably across the afforested *S. apetala* sites (Table 2). Among all the components, stems contributed the most to AGBC, ranging from 15.70 ± 15.95 t ha⁻¹ in SPD to 30.49 ± 27.90 t ha⁻¹ in MC, indicating a 94% increase. Branch biomass carbon varied from 5.47 ± 4.10 t ha⁻¹ in SPD to 10.2 ± 7.71 t ha⁻¹ in CS. Similarly, the amount of bark biomass carbon ranged from 0.93 ± 0.69 t ha⁻¹ to 1.73 ± 1.30 t ha⁻¹, and the amount of leaf biomass ranged from 0.96 ± 0.68 t ha⁻¹ to 1.81 ± 1.31 t ha⁻¹, with the minimum values in the SPD treatment and the maximum in the CS treatment. The root biomass, comprising belowground biomass (BGBC), ranged from 5.20 ± 4.96 t ha⁻¹ in SPD to 9.95 ± 8.54 t ha⁻¹ in MC, a 91.3% increase. Importantly, stem biomass contributed substantially to the AGBC at all the sites, ranging from 66.3% in the CS site to 73.5% in the MC site, with an average of more than 70% at most of the sites. This dominance indicates the key role of trunk growth in mangrove carbon storage. High standard deviations, particularly in the CS and MC, suggest variability in growth patterns due to site-specific factors. The lower contribution from leaves and bark reflects typical mangrove biomass carbon allocation.

3.2) Soil organic carbon stock (SOCS)

The spatial distribution of SOCS across the nine *S. apetala* afforested sites in Cox's Bazar is shown in Figure 5a. The SOCS values varied significantly among the sites, as indicated by one-way ANOVA ($p < 0.05$). The highest SOCS was recorded on the TP (17.42 ± 5.18 t ha⁻¹), followed closely by that on the SPD (16.08 ± 6.47 t ha⁻¹), MoC (16.06 ± 5.63 t ha⁻¹), and BU (16.04 ± 5.3 t ha⁻¹). These four sites had SOCS values exceeding 16 t ha⁻¹. Moderate levels were detected at SU (15.05 ± 5.91 t ha⁻¹) and SI (14.18 ± 6.65 t ha⁻¹), whereas the lowest SOCS values were detected at MC (13.32 ± 6.24 t ha⁻¹), NC (13.29 ± 4.88 t ha⁻¹), and CS (13.04 ± 6.17 t ha⁻¹). The difference between the highest TP and lowest CS mean SOCS was 4.38 t ha⁻¹. The variation suggests measurable spatial variability in soil carbon stocks across the afforested sites.

Table 1 Summary statistics of soil physiochemical and tree-specific parameters (mean \pm SD)

Location	Height (m)	DBH (cm)	Salinity (ppt)	pH	ToN (%)	BD (g cm ⁻³)	SOC (%)
CS	12.46 \pm 5.04	14.62 \pm 6.40	3.55 \pm 0.88	6.13 \pm 1.19	0.42 \pm 0.23	0.94 \pm 0.07	3.52 \pm 1.77
TP	14.88 \pm 5.28	19.10 \pm 8.95	3.84 \pm 1.34	6.20 \pm 1.00	0.55 \pm 0.22	0.78 \pm 0.07	5.73 \pm 1.95
SI	12.57 \pm 5.19	15.26 \pm 7.56	3.97 \pm 1.31	6.10 \pm 1.30	0.47 \pm 0.21	0.86 \pm 0.07	4.14 \pm 1.98
MoC	12.49 \pm 5.46	15.78 \pm 8.59	3.49 \pm 0.70	6.78 \pm 0.96	0.44 \pm 0.23	0.85 \pm 0.06	4.75 \pm 1.79
NC	12.90 \pm 5.19	16.39 \pm 8.17	3.80 \pm 0.88	6.41 \pm 1.21	0.48 \pm 0.28	0.87 \pm 0.05	3.88 \pm 1.57
SU	11.99 \pm 5.47	14.20 \pm 7.55	3.72 \pm 1.14	6.17 \pm 1.15	0.41 \pm 0.24	0.89 \pm 0.08	4.34 \pm 1.83
BU	12.57 \pm 6.05	17.61 \pm 10.15	3.90 \pm 1.54	6.29 \pm 1.52	0.52 \pm 0.33	0.83 \pm 0.07	4.98 \pm 2.00
SPD	13.13 \pm 5.03	16.11 \pm 7.65	3.67 \pm 0.97	6.17 \pm 1.22	0.50 \pm 0.27	0.83 \pm 0.08	5.02 \pm 2.31
MC	14.32 \pm 4.92	18.43 \pm 7.99	3.73 \pm 0.87	6.06 \pm 0.86	0.55 \pm 0.31	0.91 \pm 0.08	3.72 \pm 1.78

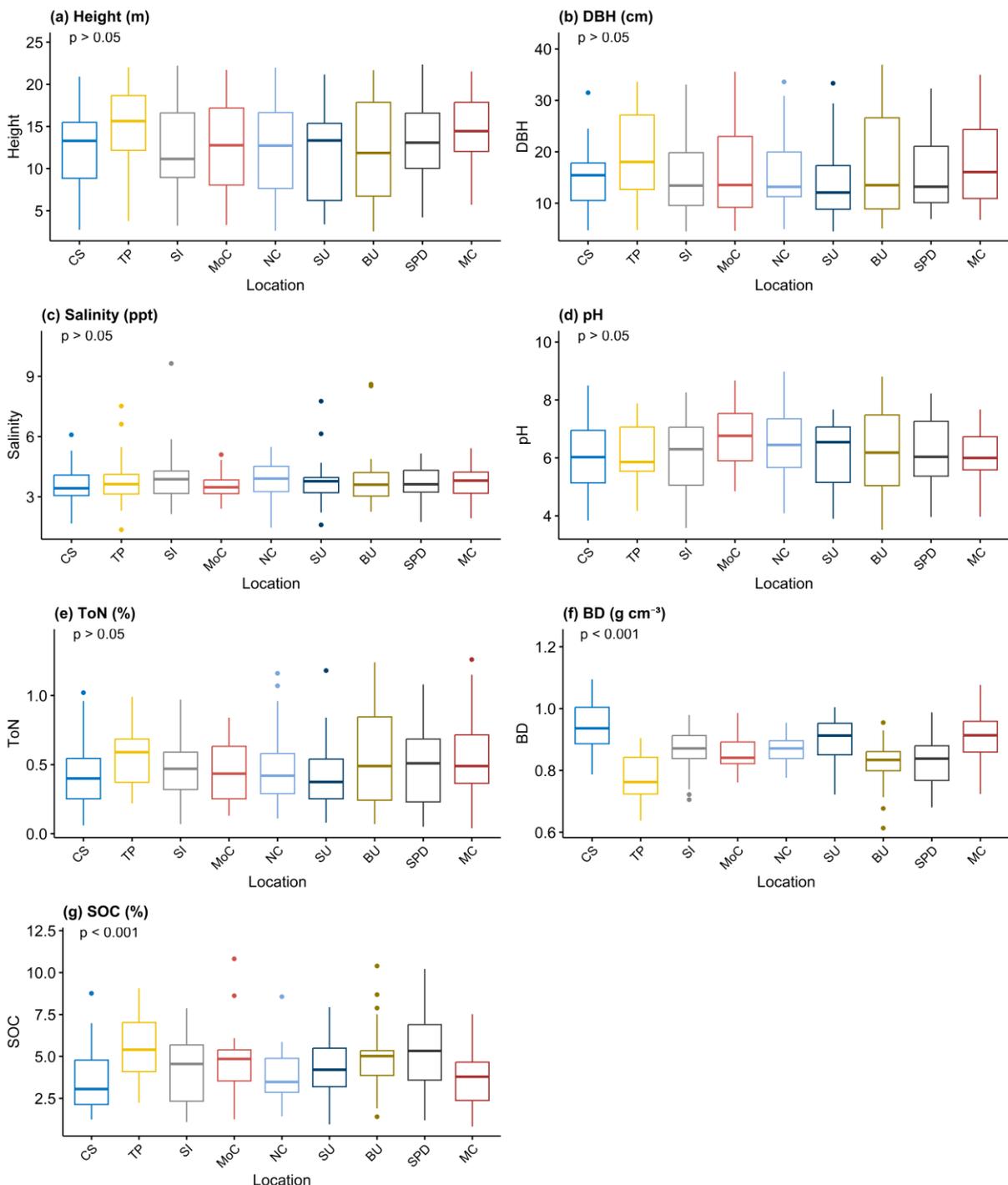


Figure 2 Variation in soil physiochemical and tree-specific parameters across different afforestation sites. One-way ANOVA indicates the degree of variability among these sites.

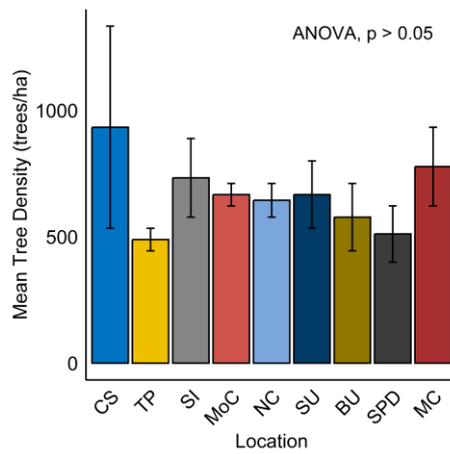


Figure 3 Mean tree density across various afforestation sites. One-way ANOVA indicated the degree of variability among these sites ($p > 0.05$).

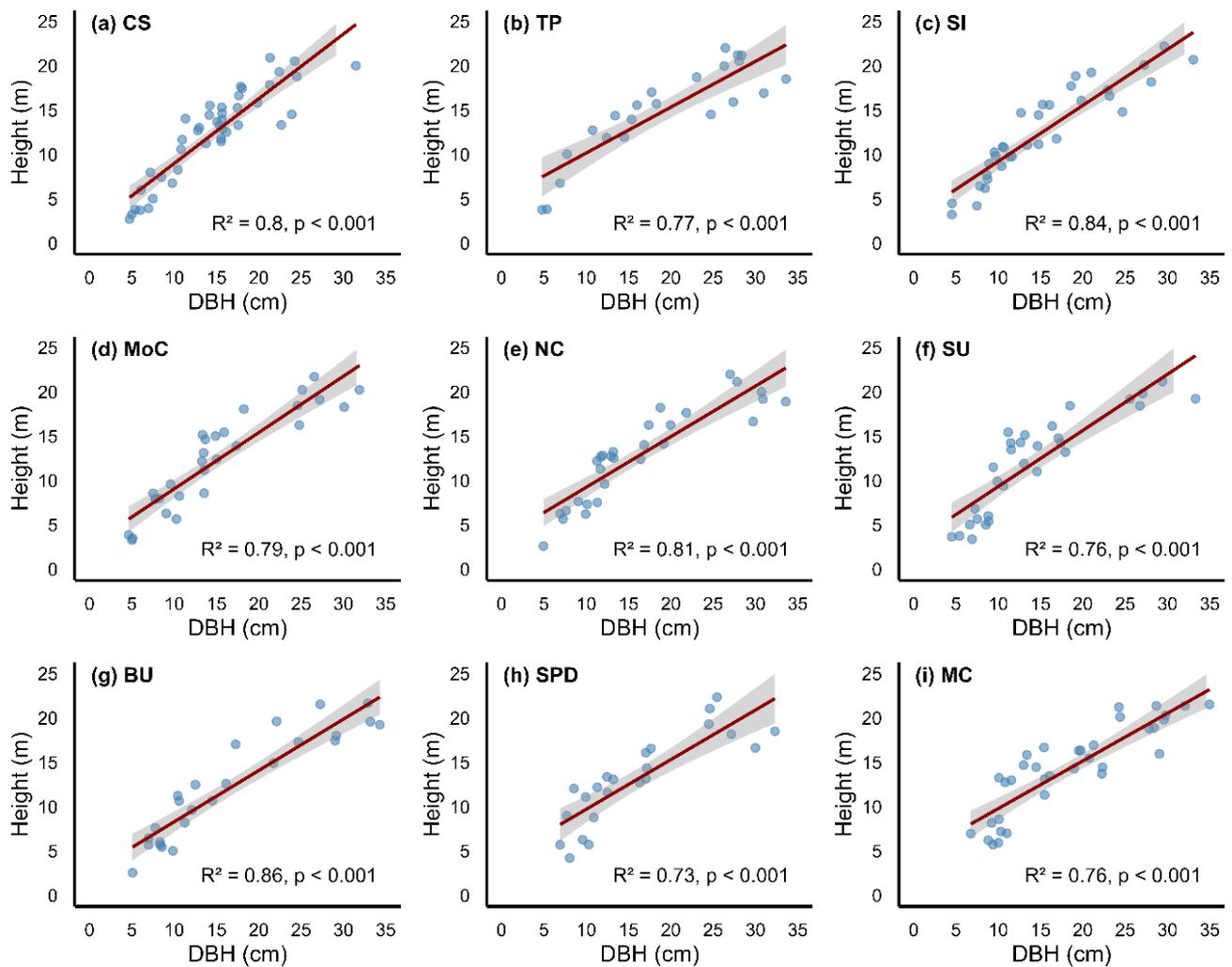
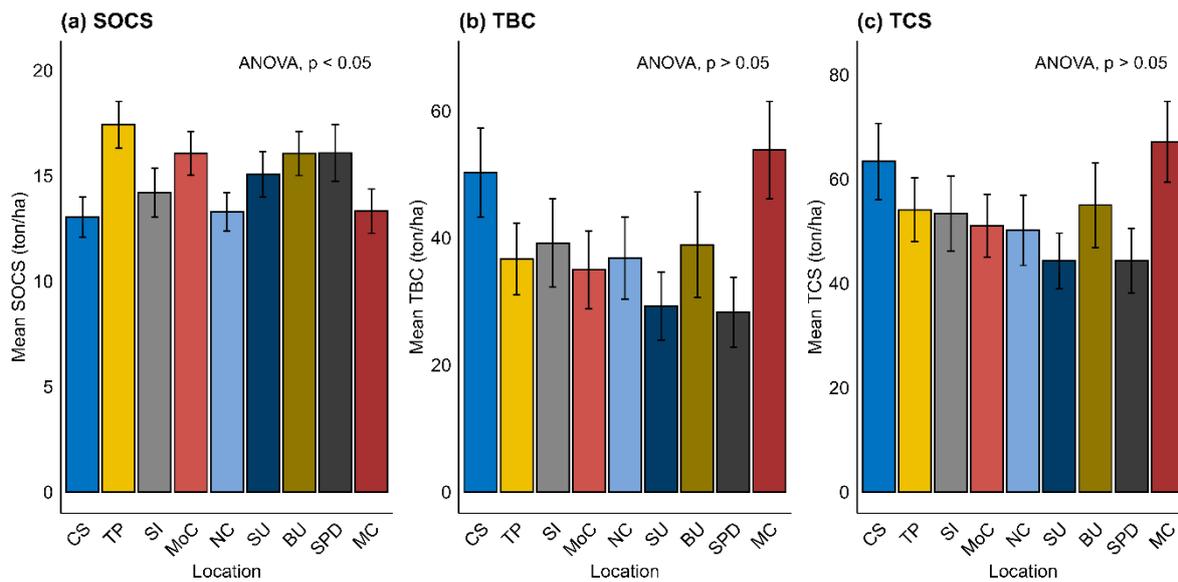


Figure 4 Relationships between the DBH and tree height of *S. apetala* across various afforestation sites.

Table 2 Biomass carbon stock (mean \pm SD, t ha⁻¹) for different plant components across various *S. apetala* afforested sites in Cox's Bazar, Bangladesh

Location	Stem	Branch	Bark	Leaf	Root	AGBC	BGBC
CS	27.35 \pm 26.76	10.2 \pm 7.71	1.73 \pm 1.30	1.81 \pm 1.31	9.24 \pm 8.50	41.09 \pm 36.93	9.23 \pm 8.50
TP	20.97 \pm 16.14	6.64 \pm 4.11	1.12 \pm 0.69	1.15 \pm 0.68	6.80 \pm 5.00	29.88 \pm 21.59	6.80 \pm 5.00
SI	21.77 \pm 24.12	7.59 \pm 6.29	1.29 \pm 1.05	1.33 \pm 1.05	7.22 \pm 7.51	31.97 \pm 32.46	7.21 \pm 7.51
MoC	19.57 \pm 20.32	6.67 \pm 5.17	1.13 \pm 0.86	1.17 \pm 0.86	6.44 \pm 6.30	28.53 \pm 27.16	6.44 \pm 6.30
NC	20.67 \pm 21.18	6.98 \pm 5.35	1.18 \pm 0.9	1.22 \pm 0.89	6.80 \pm 6.55	30.05 \pm 28.27	6.80 \pm 6.55
SU	15.99 \pm 17.75	5.86 \pm 4.57	1.00 \pm 0.77	1.04 \pm 0.76	5.36 \pm 5.51	23.89 \pm 23.78	5.36 \pm 5.51
BU	22.38 \pm 26.02	6.97 \pm 6.25	1.18 \pm 1.04	1.21 \pm 1.03	7.20 \pm 7.94	31.72 \pm 34.30	7.20 \pm 7.94
SPD	15.70 \pm 15.95	5.47 \pm 4.10	0.93 \pm 0.69	0.96 \pm 0.68	5.20 \pm 4.96	23.05 \pm 21.38	5.20 \pm 4.96
MC	30.49 \pm 27.90	9.96 \pm 6.75	1.68 \pm 1.13	1.73 \pm 1.11	9.95 \pm 8.54	43.87 \pm 36.82	9.95 \pm 8.54

**Figure 5** Spatial variation in (a) soil organic carbon stock (SOCS), (b) total biomass carbon (TBC), and (c) total carbon stock (TCS) across *S. apetala* afforested sites in Cox's Bazar. One-way ANOVA indicated significant differences among the sites for each carbon component at the 95% confidence level ($p < 0.05$).

3.3 Total biomass carbon (TBC)

The variation in TBC and the summation of AGBC and BGBC are shown in Figure 5b. The highest TBC was observed at MC (53.82 ± 45.36 t ha⁻¹), followed by that at CS (50.32 ± 45.43 t ha⁻¹). Moderate TBC values were recorded for SI (39.19 ± 34.82 t ha⁻¹), TP (36.8 ± 26.59 t ha⁻¹), NC (36.69 ± 29.28 t ha⁻¹), and BU (38.93 ± 42.24 t ha⁻¹). In contrast, SPD and SU presented the lowest TBC levels, both of which decreased below 30 t ha⁻¹. However, one-way ANOVA revealed no statistically significant difference in TBC among the sites ($p > 0.05$), although notable variation was observed. Across all the sites, AGBC made up the dominant portion of TBC, contributing between 82–85%, while BGBC accounted for the remaining 15–18%. This finding indicates the dominance of aboveground carbon pools in *S. apetala* plantations. MC resulted in the highest AGBC (43.87 t ha⁻¹) and BGBC (9.95 t ha⁻¹), whereas SPD resulted in the lowest values for both components, with AGBC occurring at 23.05 t ha⁻¹ and BGBC occurring at 5.2 t ha⁻¹ (Table 2).

3.4 Total carbon stock (TCS)

TCS, which includes both SOCS and TBC, did not vary significantly among the sites ($p > 0.05$), as shown by ANOVA (Figure 5c). The contribution of TBC to TCS was dominant across all the sites, ranging from 63.8% on the TP to 79.4% on the MC, while SOCS accounted for the remaining 20.6% to 36.2%. The highest TCS values were recorded in MC (67.15 ± 45.7 t ha⁻¹) and CS (63.37 ± 47.35 t ha⁻¹), where the biomass carbon contribution exceeded 79% and 79.4%, respectively. In contrast, the lowest TCS was observed in SPD (44.34 ± 29.51 t ha⁻¹) and SU (44.31 ± 29.02 t ha⁻¹), with TBC contributions of 63.8% and 66%, respectively. Although SOCS varied significantly across sites, the overall TCS remained statistically similar ($p > 0.05$), suggesting that variation in biomass carbon strongly influenced total carbon levels regardless of differences in soil carbon (Table 2). These results highlight the dominant role of biomass carbon in total carbon storage across the afforested *S. apetala* sites.

4) Multiple linear regression (MLR) analysis

Table 3 shows a summary of the MLR models for SOCS with pH, BD, salinity, and ToN as predictors across various afforestation sites. In modeling SOCS at the *S. apetala* afforested sites, BD emerged as the most influential predictor, with significant negative effects ($p < 0.05$), especially on the TP, MoC, NC, SU, BU, and SPD. The effects of other variables, such as pH, salinity, and ToN, varied across sites and were often statistically nonsignificant. However, some site-specific influences were observed. For example, ToN

had a significant positive and negative effect on CS and SU ($p < 0.05$), respectively. The effect of pH was significant for both SI and MoC ($p < 0.05$). Notably, all the models had relatively low R^2 values (0.029 for MC to 0.575 for SPD), indicating that a large portion of the variability in SOCS remained unexplained by the selected predictors. Moreover, scatter plots of the observed versus predicted SOCS values are shown in Figure 6, further illustrating the predictive performance of the regression models.

Table 3 Summary of multiple linear regression models for SOCS with pH, BD, salinity, and ToN as predictors across various afforestation sites

Location	Intercept estimate	pH estimate	BD estimate	Salinity estimate	ToN estimate	R ²
(a) CS	17.723	0.828	-12.516	-0.732	10.935 *	0.183
(b) TP	54.908 ***	-1.092	-33.883 *	-0.891	-1.877	0.256
(c) SI	35.654 *	-1.975 *	-12.348	-0.472	6.675	0.216
(d) MoC	29.780 *	2.565 *	-37.024 *	0.156	-0.032	0.312
(e) NC	75.519 ***	-0.633	-63.161 **	-0.918	0.366	0.399
(f) SU	47.847 ***	-0.392	-35.670 **	2.142	-16.400 **	0.392
(g) BU	47.842 ***	0.447	-41.198 **	0.057	-1.6	0.326
(h) SPD	58.463 ***	-0.188	-57.219 **	1.348	2.42	0.575
(i) MC	21.574	0.715	-12.729	-0.321	0.307	0.029

Remark: Significance levels: $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), not significant if there is no asterisk.

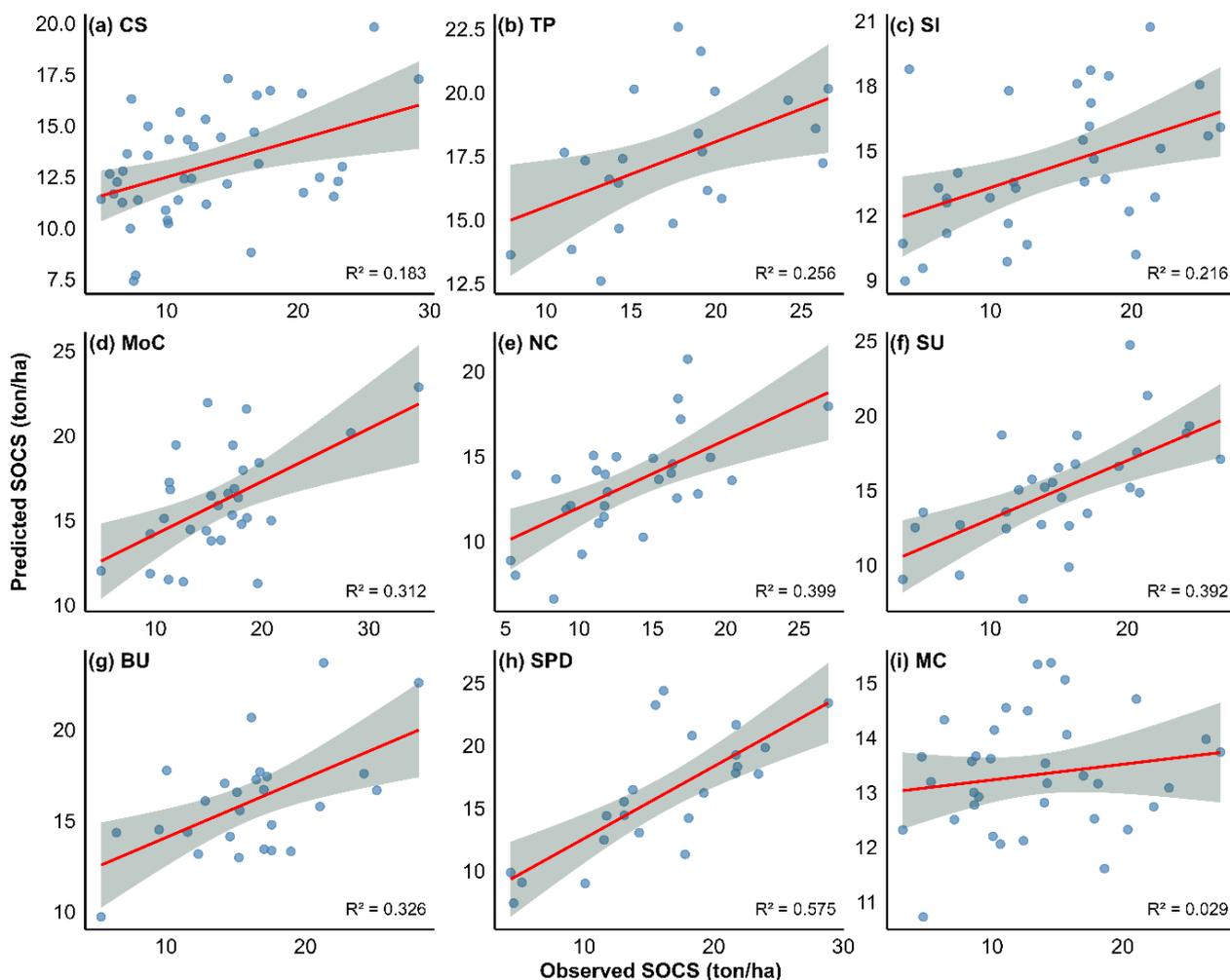


Figure 6 Model performance evaluation for total SOCS estimation using pH, BD, salinity, and ToN as predictors across various afforestation sites.

Discussion

1) Influence of tree growth and soil properties on carbon accumulation patterns

Mangrove biomass carbon accumulation is influenced by both tree-specific and soil properties, although the degree of influence varies across species and locations (Ahmed et al., 2024a; Kamruzzaman et al., 2017). In coastal Bangladesh, soil factors such as pH, salinity, and nutrient availability also influence mangrove growth and carbon accumulation (Ahmed et al., 2022b; Rahman, 2020). For example, Islam et al. (2022) reported reductions in height, DBH, basal area, and TBC in dominant Sundarbans species under relatively high salinity. Similarly, Dasgupta et al. (2017a) assessed the projected impacts of climate change and aquatic salinization on several mangrove species in the Bangladesh Sundarbans. Their modeling predicted substantial species losses for *Heritiera fomes* (the dominant species), potential population gains for *Excoecaria agallocha*, and mixed impacts for other species, indicating varied adaptive responses to increasing salinity stress. In contrast, the present study revealed weak correlations between salinity, pH, and TCS (Figure 7; Table 3), suggesting that *S. apetala* has high salt tolerance and adaptability to dynamic soil conditions. This may be due to the relatively lower salinity and pH levels in Cox's Bazar than in other plantation sites, such as Noakhali, Bhola, Patuakhali, and Satkhira (Hossain et al., 2012), potentially due to differences in tidal regimes, freshwater inflow, and soil composition (Baten et al., 2015).

The SOCS can vary widely across regions worldwide and even among different locations within the same study area because of differences in vegetation, hydrology, and land use conditions (Ahmed et al., 2024a). In the present study, the SOC concentration was greater at the TP, BU, SPD, and MoC sites than at the other sites. This may be due to local differences in forest structure and site conditions rather than broad regional factors. These sites have denser tree cover, which may increase the amount of leaf litter and root biomass inputs to the soil (Ismail et al., 2025). They are also situated in more sheltered tidal environments where fine sediments accumulate and water remains for longer periods, promoting carbon burial. In addition, low levels of human disturbance and limited soil mixing reduce carbon loss (Kamruzzaman et al., 2017). Together, these local conditions favor higher SOCS at the TP, BU, SPD, and MoC sites.

The unique environmental setting of mangrove forests also affects their nutrient dynamics (Alongi, 2012; 2014). In this study, TCS was positively correlated with SOC ($r = 0.21$, $p < 0.001$) and ToN ($r = 0.77$, $p < 0.001$) (Figure 7), indicating that biomass carbon storage is significantly influenced by soil nutrient availability, similar to the findings of Ismail et al. (2025) and Ahmed et al. (2024a) in *S. apetala* plantations in

Bangladesh. Increased SOC may also result from increased input of carbon to soils from fallen leaf litter (Liu et al., 2017) and the turnover of dead roots (Arnaud et al., 2023; Zhang et al., 2021). Conversely, soil BD was negatively correlated with TCS ($r = -0.15$; $p < 0.05$), suggesting that increased soil compaction may hinder root development and microbial processes, ultimately reducing soil carbon sequestration (Yu et al., 2020). The higher BD may also be related to sandy soil types, which hold less organic carbon because they have a lower mineral surface area for carbon adsorption than clayey soils with lower BD (Kleber et al., 2021). Additionally, significant interrelationships were observed between key tree and soil variables, such as SOC and BD ($r = -0.58$), DBH and ToN ($r = 0.84$), and DBH and height ($r = 0.89$), all at $p < 0.001$. These interactions underscore the functional relationship between tree structural attributes and soil conditions in regulating the carbon storage potential of mangrove ecosystems. Moreover, the correlation between BD and BGBC ($r = -0.1$) was not significant ($p > 0.05$) in this study, indicating that soil BD primarily influences SOC rather than carbon stored in roots. These findings also suggest that BD controls carbon variability mainly in the soil rather than in terms of plant biomass.

Although the effects of latitude, distance from the ocean, and geomorphological setting were not explicitly tested in this study, the observed patterns suggest that these spatial gradients may play important roles. Sites more distant from the open coastline and within sheltered geomorphic settings receive less hydrodynamic energy, enhancing fine sediment deposition and organic matter retention, resulting in lower BD and higher SOC (Dookie et al., 2023). In contrast, sites closer to the ocean face stronger tidal flushing and wave action, promoting sediment resuspension and coarser textures, which lead to higher BD and reduced SOC accumulation. Latitudinal differences among sites may influence salinity regimes, pH, ToN, and vegetation productivity, indirectly affecting soil carbon inputs and stabilization processes (Kang et al., 2024; 2026). These interpretations indicate potential underlying mechanisms that need further examination through focused spatial analyses.

2) Comparative analysis of the TCS across various forest ecosystems

The estimated mean TCS in the afforested *S. apetala* mangrove site of Cox's Bazar was 53.64 t ha^{-1} (Table 4), which is considerably lower than that in many other mangrove ecosystems. For example, afforested *S. apetala* forests in Teknaf, Bangladesh, and Qi'ao Island, China, recorded much higher TCS values of 125.52 t ha^{-1} (Miah and Hossain, 2021) and 149.28 t ha^{-1} (Yu et al., 2020), respectively. Natural mixed mangrove forests, such as those in Kerala, India (139.82 t ha^{-1} ,

(Harishma et al., 2020)), and the Sundarbans in Bangladesh (80 t ha⁻¹, (Ray et al., 2011)), also have higher carbon stocks. The SOCS estimated in the present study represents only the surface 0–40 cm soil layer. This depth is shallower than the ≥1 m depth commonly recommended for comprehensive blue carbon assessments (Cooray et al., 2024; Dahl et al., 2025). Consequently, the SOCS values reported here are likely

underestimated, which may partly explain the relatively higher proportional contribution of TBC than that of soil carbon observed in this study. However, in global mangrove assessments, SOCS often dominates the TCS (Alongi, 2020). Therefore, comparisons with other mangrove and terrestrial forest ecosystems should be interpreted cautiously, particularly where soil sampling depths differ (Table 4).

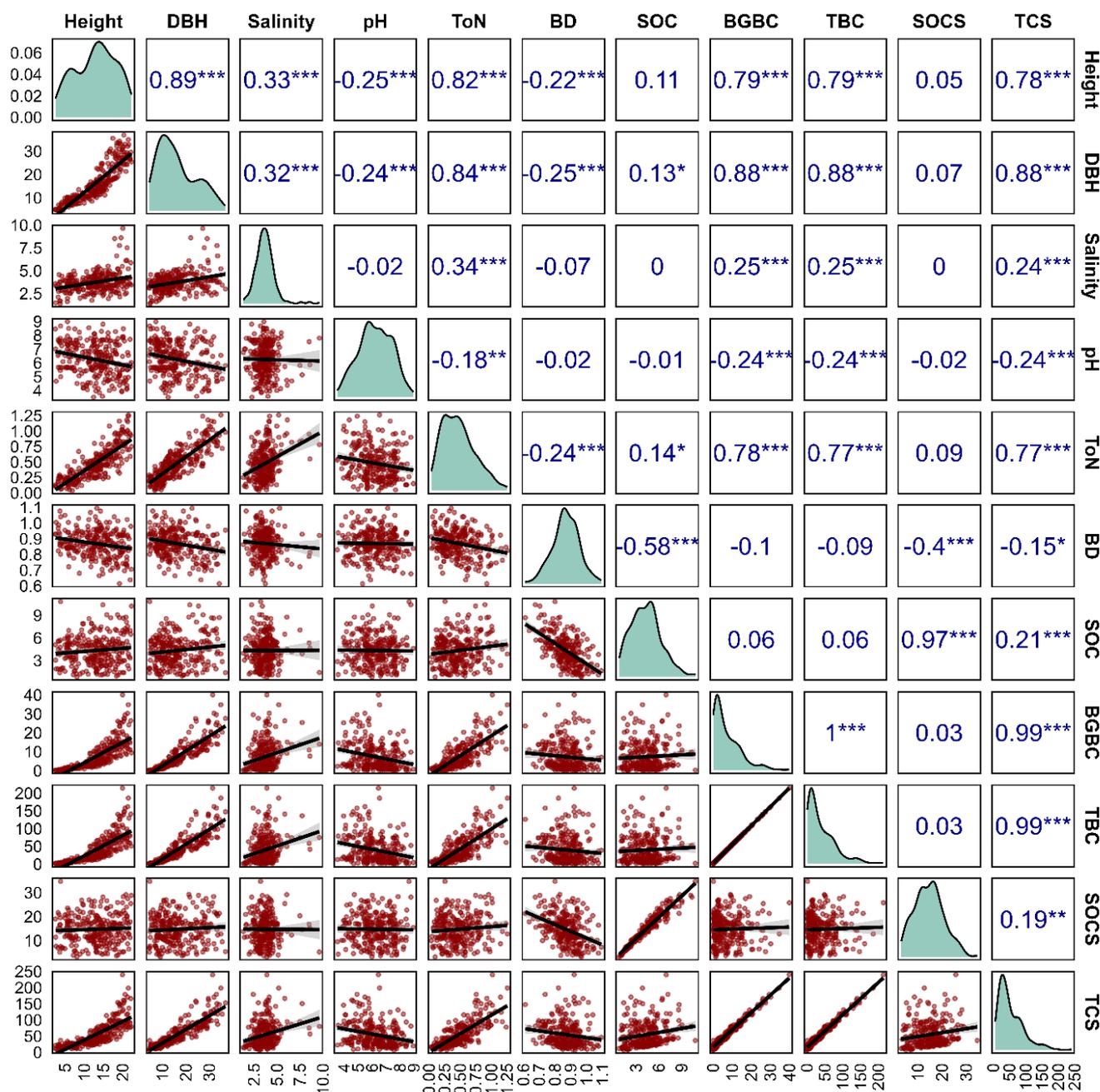


Figure 7 Scatterplot matrix showing pairwise relationships among tree structure, soil properties, and carbon stock variables at the *S. apetala* afforested sites. The upper panels show Pearson's correlation coefficients, with significance levels indicated as follows: *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$. The lower panels include regression lines with 95% confidence intervals.

Table 4 Summary of SOCS, TBC, and TCS in various forest ecosystems across the world

Mangroves	Coordinate	Forest types	Soil depth (cm)	SOCS	TBC	TCS	References
				t ha ⁻¹			
Cox's Bazar, Bangladesh	20°43' to 21°56' N, 91°50' to 92°23' E	Afforested <i>S. apetala</i>	0–40	14.94	38.70	53.64	This study
Chakaria Sundarbans, Bangladesh	21°36'15" to 21°44'25"N	Afforested <i>S. apetala</i>	0–30	69.29	53.30	122.59	Ismail et al. (2025)
Kerala Mangroves, India	10° 51' 1.8576" N, 76° 16' 15.8880" E	Natural mixed	0–60	81.26	58.56	139.82	Harishma et al. (2020)
Teknaf forest range, Bangladesh	21°10' N to 20°40' N, 92°05' E to 92°25' E	Afforested <i>S. apetala</i>	0–30	35.61	89.91	125.52	Miah and Hossain (2021)
Qi'ao Island, China	22°23'40" to 22°27' 38"N, 113°36' 40" to 113°39'15"E	Afforested <i>S. apetala</i>	0–100	86.28	63.00	149.28	Yu et al. (2020)
Maogang, Mangroves, China	110°54'E, 21°27' N	Afforested <i>S. apetala</i>	0–100	43.24	10.42	53.66	Wang et al. (2013)
Subtropical evergreen broad-leaved forest Asia-Pacific	21° 31' to 23°10' N, 112° 45' to 113° 50' E	Natural mixed	0–100	89.28	118.57	207.85	Sun et al. (2014)
Cilacap, Indonesia	8° S to 22° N, 90° to 163° E	Natural mixed	0–300	783.50	239.50	1023.00	Donato et al. (2011)
Sundarbans, Bangladesh	7°43'25"S, 108°57'29"E	Natural mixed	0–300	571.60	21.20	592.80	Murdiyarso et al. (2015)
Zambezi River Delta, Mozambique	21°32'N, 88°55'E	Natural mixed	0–60	26.00	54.00	80.00	Ray et al. (2011)
	18°36'S, 35°51'E	Natural mixed	0–200	283.00	200.00	483.00	Stringer et al. (2015)

Additionally, the lower carbon stock in Cox's Bazar can largely be attributed to the monoculture afforestation of *S. apetala*, which inherently sequesters less biomass and soil carbon than diverse natural mangrove stands do (Rahman et al., 2015). Monoculture plantations typically have lower structural complexity and limited species diversity, which are essential for greater carbon accumulation (Alongi, 2012; Donato et al., 2011). Additionally, the low tree density at these afforested sites resulted in lower overall biomass and soil carbon (Figures 3 and 5), directly reducing the total carbon stock per hectare. In addition to ecological factors, anthropogenic influences and environmental disturbances critically contribute to low carbon stocks. Cox's Bazar coastal area experiences frequent human interventions, such as timber harvesting, land use changes, shrimp farming, and local resource extraction, which degrade forest integrity and reduce biomass and soil carbon pools (Ahmad, 2019; Dutta and Hossen, 2020; Hoque and Datta, 2005; Prince et al., 2018; Siddiqui and Rahman, 2020). Furthermore, the region is vulnerable to extreme weather events, including cyclones and tidal surges, which physically damage mangrove vegetation and cause biomass losses (Islam, 2014; Shampa et al., 2023). These repeated disturbances limit forest maturity and recovery, constraining carbon sequestration capacity. Environmental conditions such as soil quality, salinity, and nutrient availability

also play crucial roles. The relatively low SOCS in Cox's Bazar (14.94 t ha⁻¹) (Table 4) suggests that edaphic factors may be less favorable for organic matter accumulation and retention (Miah and Hossain, 2021). Moreover, the afforested mangroves are relatively young and likely have not yet reached their maximum biomass potential, as carbon accumulation in mangroves has increased over decades.

In addition to ecological and environmental constraints, it is important to contextualize the carbon sequestration potential of *S. apetala* plantations within the broader landscape of forest ecosystems in Bangladesh. Several studies have highlighted the carbon sequestration potential of various forest types across Bangladesh. For example, protected forests in northeastern Bangladesh store between 58.2 and 72.9 t ha⁻¹ of carbon (Saimun et al., 2021), whereas homestead forests on Maheshkhali Island and in northern Bangladesh store approximately 46 t ha⁻¹ (Baul et al., 2021) and 53.53 t ha⁻¹ (Jaman et al., 2016), respectively. In comparison, in the current study, the TCS values recorded in afforested *S. apetala* ranged from 44.34 in SU to 67.15 t ha⁻¹ MC. These results suggest that afforested *S. apetala* sites can achieve carbon storage levels comparable to those of many terrestrial forests in Bangladesh, indicating their important role in climate change mitigation.

3) Implications for mangrove afforestation practices and climate change mitigation

Bangladesh, as a low-lying deltaic country, has long recognized the ecological and socioeconomic value of mangroves, especially in disaster-prone coastal areas (Dasgupta et al., 2017b; Mahmood et al., 2023). National strategies such as the Bangladesh Climate Change Strategy and Action Plan (2009), Coastal Greenbelt Project (2005), National Adaptation Plan of Bangladesh (2023–2050), and the Delta Plan 2100 prioritize mangrove restoration as a part of ecosystem-based adaptation (ADB, 2005; GED, 2018; MoEF, 2009; MoEFCC, 2022). The government of Bangladesh has actively promoted the afforestation of mangrove species, particularly in vulnerable coastal zones such as Cox's Bazar, to increase resilience against sea level rise, storm surges, soil erosion, and salinity intrusion (MoEFCC, 2018). Findings from the present study strongly align with these national objectives. The high TBC and SOCS observed in certain *S. apetala* plantations demonstrate the dual climate mitigation and ecological benefits of mangrove afforestation. Therefore, overall plantation health and site-specific practices should be prioritized in terms of mangrove management to increase biomass accumulation, soil carbon storage, and overall ecosystem services (Schmitt et al., 2016; Uddin et al., 2022). Additionally, AGBC contributed more than 80% of the TBC across sites, indicating that maximizing vegetative growth can yield faster carbon benefits than soil carbon in early-stage plantations. In coastal regions such as Cox's Bazar, where exposure to cyclones, tidal surges, and coastal erosion is severe, mangrove afforestation serves not only as a carbon sequestration strategy but also as a protective green infrastructure (Islam et al., 2015b). The natural wave attenuation and sediment stabilization functions of mangroves have been documented during extreme events, such as those reported by Cyclone Sidr (2007) and Amphan (2020), where areas with dense mangrove cover sustained significantly less damage. Additionally, the integration of community-based co-management in afforestation programs further ensures long-term stewardship and socioeconomic benefits, including alternative livelihoods (Islam et al., 2015b; Rasmee-masuang and Sasaki, 2015; Zamboni et al., 2022; Zhou et al., 2022). These findings reinforce the need to expand and sustain mangrove afforestation as a climate-resilient solution, which is closely aligned with Bangladesh's National Adaptation Plan (NAP) and broader sustainable development goals.

4) Limitations of the study and directions for future research

This study provides valuable insights into carbon accumulation at afforested *S. apetala* sites in Cox's

Bazar; however, several limitations must be acknowledged. Soil samples were collected only up to a depth of 40 cm, potentially underestimating total SOCS, as deeper layers can store significant amounts of carbon over the long term. Moreover, the soil samples were homogenized as composite samples for the 0–40 cm depth, which restricted the assessment of vertical (downcore) variation in soil physicochemical properties and carbon distribution. Additionally, only trees with a DBH greater than 4.5 cm were considered, which may exclude younger or smaller individuals who contribute to regeneration and early-stage carbon dynamics. Litterfall, a key component of nutrient cycling and an important contributor to soil organic matter, was also not included in this assessment, possibly leading to an underestimation of total carbon input. Furthermore, the study did not account for temporal variations or environmental disturbances, such as seasonal salinity shifts and extreme weather events, which can significantly influence biomass and soil carbon stocks. Future research should aim to incorporate depth-segmented soil sampling to capture downcore variability, along with deeper soil profiles, all tree size classes, litterfall quantification, and time series or remote sensing analyses, to increase the accuracy of carbon stock estimations and better inform mangrove afforestation strategies under changing climatic conditions.

Conclusions

This study examined the variation in TCS in *S. apetala*-afforested mangroves along Cox's Bazar coast, Bangladesh. Biomass carbon was dominated by stand stems, contributing more than 70% of the aboveground carbon stock. The SOCS varied among the sites, with the highest values observed for TP, SPD, MoC, and BU. This was likely due to higher litterfall, greater root turnover, and reduced human disturbance. BD emerged as the most influential soil property controlling SOC and was strongly negatively correlated. Other soil factors, including pH, salinity, and ToN, had site-specific effects on SOCS. Despite the variation in SOCS, TCS did not differ significantly among the sites, highlighting the dominant role of biomass carbon in total storage. These results suggest that in terms of mangrove management, biomass accumulation through well-established plantations should be prioritized. Maintaining favorable soil conditions to reduce compaction and enhance organic matter retention is also essential. Site selection based on tidal exposure and sediment deposition patterns can further improve carbon sequestration. Implementing these strategies can strengthen the climate mitigation potential of *S. apetala* plantations and increase the sustainability of coastal mangrove ecosystems in Bangladesh.

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Data availability statement

Information and data used in the study will be disclosed upon request.

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Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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