BEFORE THE NATIONAL GREEN TRIBUNAL (SOUTHERN ZONE)

AT CHENNAI

(Under Sections 14 and 15 read with 18 (1) of the National Green Tribunal Act, 2010)

Original Application No. 65 of 2025

Ramaniyam Towers Residents Association,

Represented by Mr. Kannan Subbiah,

Authorized Representative …Applicant

v.

Tamil Nadu Coastal Zone Management Authority

Represented by its Member Secretary …Respondents

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Research article

A case study on structural development and ecological services of restored mangroves in Adyar Estuary, India

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Mangroves, critical coastal wetlands, face global degradation, necessitating conservation and restoration efforts. This study evaluates mangrove restoration in the Adyar Estuary, Chennai, along the Bay of Bengal, degraded by urbanization and anthropogenic pressures. It evaluates afforested mangroves' structural development, restored ecological functions, and factors enabling their establishment. Spanning 56.6 acres, the estuary hosts six mangrove species, with *Avicennia marina* dominant. The afforested mangroves showed a median density of 3900 trees ha^{-1}, vegetation biomass of 222.26 Mg ha^{-1}, and carbon stock of 99.89 Mg C ha^{-1} (366.60 Mg CO_2e ha^{-1}). Total carbon storage was 2288.00 Mg C (8397.05 Mg CO_2e), with annual sequestration at 325.71 Mg C year^{-1} (1195.42 Mg CO_2e year^{-1}). Reduced self-thinning indicated enhanced self-tolerance. Despite pollution, mangroves thrived due to locally adapted species, replanting efforts and community involvement. This study highlights mangrove restoration as a strategy for climate resilience, aligning ecological and socio-economic goals.

Keywords: Carbon sequestration, climate resilience, ecological services, mangroves, restoration

Introduction

Mangroves are forested intertidal wetlands that provide a variety of ecological services, including provisioning, supporting, regulating, and cultural services (Himes-Cornell et al. 2018). Globally, mangroves experience both losses and gains, driven by land-use changes and urban expansion on one hand, and conservation and restoration efforts on the other (Hagger et al. 2022, Wei et al. 2024). Mangrove degradation raises awareness and attracts legal protection to conserve and manage them sustainably. In this context, mangrove restoration and rehabilitation have become increasingly important concerns (Lovelock et al. 2022). Mangrove restoration has gained prominence in many global initiatives, including the United Nations Decade on Ecosystem Restoration (2021–2030), the 2030 Agenda for Sustainable Development, the Global

Mangrove Alliance, and the Mangrove Alliance for Climate, to name a few. Many countries, including India, are restoring mangroves to support livelihoods, protect habitats, boost biodiversity, and combat climate change (Bayraktarov et al. 2016, Kathiresan 2023).

In India, mangrove restoration activities have been attempted in the Adyar Estuary of Chennai along the Bay of Bengal. Chennai is a coastal metropolitan city and the capital of Tamil Nadu. The city is traversed by the Adyar and Cooum rivers. The estuary supported littoral vegetation, including mangroves, psammophytes, freshwater aquatics, and dry evergreen forests, thriving due to soil salinity, humidity and proximity to the sea (Karthigeyan et al. 2013). However, the Adyar Estuary and adjoining creek have lost their native condition and been under severe ecological stress for decades due to urbanisation, encroachment, dumping of untreated sewage and solid waste, industrial effluents and stormwater runoff from the city (Janakiraman et al. 2017, Altaff et al. 2019). These anthropogenic pressures significantly damaged the mangroves along the edges and islands of the estuary, which had an aerial cover of 48 ha (118.6 acres) in the 1980s (Selvam et al. 1991), leaving only sparse populations of *Avicennia marina* by the 2000s (Ramanujam et al. 2014).

In response, the Government of Tamil Nadu established the Chennai Rivers Restoration Trust (CRRT) in 2006 with the goal of preserving and restoring the wetland. Along the creek banks and islands of the estuary, invasive alien plant *Neltuma juliflora* (formerly *Prosopis juliflora*) were removed and replaced with native mangroves and other suitable coastal vegetation (Adyar Poonga Trust 2008). The CRRT completed eco-restoration of 58 acres in phase I (2008 to 2010) with the development of an Eco Park (Adyar Poonga) and 300 acres in phase II (2010) in the estuarine region, restoring its ecosystem services (CRC 2019).

Assessing the effectiveness of restoration measures is essential for evaluating the restoration of ecosystem services in rehabilitated areas and guiding future mangrove restoration efforts (Kodikara et al. 2017). The objectives of this study were to: 1) evaluate the structural development of the afforested mangroves in the Adyar Estuary; 2) identify the ecological functions restored through mangrove restoration; and 3) determine the factors contributing to the successful establishment of the afforested mangroves. This assessment will support future mangrove restoration efforts by providing valuable knowledge, particularly for large-scale initiatives like the Mangrove Initiative for Shoreline Habitats & Tangible Incomes (MISHTI) programme, which aims to expand India's mangrove cover to approximately 540 km^2.

Material and methods

Study area

The Adyar Estuary and Creek span 358 acres (CRC 2019). The Adyar Estuary (Fig. 1) is a highly productive transition zone with significant commercial importance (Raja et al. 2019). It experiences a tropical wet and dry climate with a mean annual rainfall of 1400 mm. During May and June, summer temperatures range from 38 to 42°C, while in December and January, they range from 18 to 20°C (Rubalingeswari et al. 2021). The northeast monsoon (September to November) brings rainfall to the region, and relative humidity levels range from 63% to 86%. Sandbars frequently form at the estuary's mouth, hindering tidal water exchange, stagnating the water column, and impacting the physio-chemical parameters. Additionally, the estuary is severely contaminated due to the discharge of uncontrolled industrial effluents (Raja et al. 2019).

Mapping of mangroves

Extensive mangrove afforestation was carried out by CRRT along the creek banks and islands of the Adyar Estuary over various years between 2008 and 2016 (Oppili 2016, Janakiraman et al. 2017). The planted native mangrove species included *Aegiceras corniculatum*, *Avicennia* spp., *Bruguiera cylindrica*, *Excoecaria agallocha* and *Rhizophora* spp. (Adyar Poonga Trust 2008, Idea Design 2020). Mangrove plantations covered a total area of 40 acres (16.19 ha) within the estuary and creek (ICSF 2016). The restoration project was based on zonation principles to match the ecological preferences of different mangrove species. *Rhizophora* spp. were planted along the water front, allowing them to tolerate regular inundation (Adyar Poonga Trust 2008). A mixed plantation of *Avicennia* spp., *Aegiceras corniculatum* and *Bruguiera cylindrica* was established next to *Rhizophora* spp., while *Excoecaria agallocha* was planted in interior parts, ensuring species placement was consistent with their ecological requirements. To map the current extent of mangroves, cloud free Sentinel-2 multispectral images with a 10 m spatial resolution were collected for the study area during 2022. Ground control points were gathered to verify the presence of mangroves and served as training data for the classifier. Google Earth Engine was used to categorise mangroves efficiently using the classification and regression trees (CART) classifier approach. The present study did not estimate the mangrove extent in the 1980s or the initial mangrove restoration in 2008 due to potential inaccuracies in area estimates resulting from the coarse resolution of freely available satellite images. For the comparison of mangrove cover change, the pre-existing mangrove cover value from the 1980s (118.6 acres, Selvam et al. 1991) was used as a reference in the current study.

Vegetation assessment

Field surveys were conducted at nine stations (Fig. 1) with a minimum spacing of 50 m between them along the Adyar Estuary and Creek during August 2022 to assess the vegetation structure of the afforested mangroves. At each station, random plots measuring 10 × 10 m were established to study the vegetation characteristics of the afforested mangroves (Ragavan et al. 2021a). A total of 49 sampling plots were used, and the age of the mangrove stands in each station

Figure 1. Study area – Adyar Estuary in Chennai (numbers indicate stations. Insert map is approved coastal zone management plan for the year 2011 (GoT-DoE 2024).

was determined based on information provided by CRRT (Table 1).

Within each sampling plot, all mangroves were identified (Ragavan et al. 2021b) and counted. Girth at breast height (GBH) and tree height were measured using a distometer (Leica Disto D510). Based on these data, basal area ($m^2\,ha^{-1}$) and stand density (stems ha^{-1}) were calculated. The importance value index (IVI), a relative measurement of a species' ecological contribution, was determined by summing its relative density, relative frequency and relative dominance. Non-destructive sampling methods were employed, ensuring that no trees were cut down.

$$\text{Relative density}(\%) = \frac{\text{Number of individuals of a species}}{\text{total number of individuals of all species}} \times 100 \quad (1)$$

$$\text{Relative frequency}(\%) = \frac{\text{Frequency of a species}}{\text{Sum of frequency of all species}} \times 100 \quad (2)$$

$$\text{Relative dominance}(\%) = \frac{\text{Basal area of a species}}{\text{Sum of basal area of all species}} \times 100 \quad (3)$$

$$\text{IVI}(\%) = \text{Relative density} + \text{Relative frequency} + \text{Relative dominance} \quad (4)$$

Vegetation biomass and carbon stock estimation

In the present study, two carbon pools, namely above-ground vegetation biomass (AGB) and below-ground vegetation biomass (BGB), were considered to measure the vegetation carbon stock of the afforested mangroves in the estuary. The allometric equations (Eq. 5 and 6) for Southeast Asian mangroves (Komiyama et al. 2005) were applied to estimate AGB and BGB.

$$\text{AGB} = 0.251 \times r \times \text{D}^{2.46} \quad (5)$$

$$\text{BGB} = 0.199 \times r^{0.899} \times D^{2.22} \quad (6)$$

Table 1. Importance value index (IVI) for different species in the Adyar Estuary, Chennai. n = number of quadrats studied for each station. * = 6-year-old stand; # = 14-year-old stand; $ = 22-year-old stand; ¥ = Mixed (6-, 17- and 21-year-old stands). Abbreviations: Ac = *Aegiceras corniculatum*; Am = *Avicennia marina*; Ao = *Avicennia officinalis*; Bc = *Bruguiera cylindrica*; Ea = *Excoecaria agallocha*; Rm = *Rhizophora mucronata*.

	IVI (%)					
Station	Ac	Am	Ao	Bc	Ea	Rm
Station 1 (n = 2)*	19.73	14.29	17.19	14.29	211.47	23.04
Station 2 (n = 11)*	–	89.09	–	–	148.78	62.13
Station 3 (n = 2)*	–	–	–	–	300.00	–
Station 4 (n = 6)#	–	300.00	–	–	–	–
Station 5 (n = 4)$	–	266.66	–	–	33.34	–
Station 6 (n = 7)¥	–	208.27	–	–	91.73	–
Station 7 (n = 5)*	–	105.86	–	–	182.75	11.39
Station 8 (n = 7)*	–	178.19	–	–	121.81	–
Station 9 (n = 5)*	–	244.23	–	–	55.77	–
Overall estuary (n = 49)	1.33	170.58	1.28	1.23	107.80	17.77

where, AGB is the above-ground vegetation biomass (kg), BGB is the below-ground vegetation biomass (kg), r is the species' wood density, and D is the diameter derived from GBH using Eq. 7.

$$D = \frac{\text{GBH}}{(22/7)} \quad (7)$$

The wood density for the afforested mangrove species present in the estuary (Table 2) was obtained from the Global Wood Density Database (Zanne et al. 2009). The high coefficient of determination ($R^2 > 0.9$) of these allometric equations (Komiyama et al. 2005) attests to their good fit. The allometric measurement method was selected because it is one of the best methods for estimating biomass and carbon stocks without requiring the harvesting of mangroves or field validation of data obtained from remote sensing (Pati et al. 2022). Although these equations were developed using Southeast Asian mangrove forests, their application is justified for this study due to the notable similarities between Indian and Southeast Asian mangroves (Ragavan et al. 2016). These allometric equations have also been applied to estimate the biomass and carbon stock of mangroves in India (Ragavan et al. 2021a).

All biomass values were expressed as Megagrams per hectare (Mg ha^{-1}). The total mangrove vegetation biomass for the afforested mangroves (Mg ha^{-1}) was obtained by summing the AGB and BGB. The carbon stock (Mg C ha^{-1}) of above- and below-ground vegetation biomass was calculated by multiplying the biomass values for AGB by 0.48 and for BGB by 0.39 (Kauffman and Donato 2012), and then summing them to estimate the total vegetation carbon stock in the afforested mangrove stands. The calculated total afforested mangrove vegetation carbon stock was converted into CO_2 equivalent (Mg CO_2e ha^{-1}) using a factor of 3.67 (Kauffman and Donato 2012). Annual rates of vegetation biomass accumulation, carbon sequestration, and CO_2 equivalent sequestration were calculated using Eq. 8, 9 and 10, respectively.

$$\text{Biomass accumulation rate}\left(\text{Mg ha}^{-1}\ \text{year}^{-1}\right) = \frac{\text{Total vegetation biomass}\left(\text{Mg ha}^{-1}\right)}{\text{Age of mangrove stand}\left(\text{years}\right)} \quad (8)$$

$$\text{Carbon sequestration rate}\left(\text{Mg C ha}^{-1}\ \text{year}^{-1}\right) = \frac{\text{Total carbon storage}\left(\text{Mg C ha}^{-1}\right)}{\text{Age of mangrove stand}\left(\text{years}\right)} \quad (9)$$

$$\text{CO}_2\text{e sequestration rate}\left(\text{Mg CO}_2\text{e ha}^{-1}\ \text{year}^{-1}\right) = \frac{\text{Total CO}_2\text{e}\left(\text{Mg CO}_2\text{e ha}^{-1}\right)}{\text{Age of mangrove stand}\left(\text{years}\right)} \quad (10)$$

Data analysis

In the present study, stand density, basal area, AGB, BGB, total vegetation biomass, as well as their carbon stocks, CO_2e, and annual accumulation rates, were assessed in the afforested mangroves of the estuary. The afforested mangrove stands at the nine stations were analysed for statistical differences using these variables. The Shapiro–Wilk test for normality was used to confirm that the data for these variables were not normally

Table 2. Wood density for different mangrove species in the Adyar Estuary, Chennai

Mangrove species	Wood density (g cm^{-3}, oven dry mass/fresh volume)
Aegiceras corniculatum	0.510
Avicennia marina	0.650
Avicennia officinalis	0.620
Bruguiera cylindrica	0.720
Excoecaria agallocha	0.380
Rhizophora mucronata	0.740

distributed, and the Kruskal–Wallis test was then applied to compare the median values of these variables among the nine stations. Tree diameter at breast height (DBH) was divided into seven size categories: 1–5, > 5–10, > 10–15, > 15–20, > 20–25, > 25–30, and > 30 cm, and their stem densities were determined and compared among the stations. Further, the relationship between tree DBH (cm) and tree height (m) was plotted and compared.

We used a log–log scale to plot the mean individual tree total biomass, mean individual AGB, and mean individual BGB against the tree density of the mangrove stand to describe their relationship and evaluate competition caused by overcrowding. The self-thinning rule states that in overcrowded stands, a linear correlation exists between plant biomass and stem density (Vospernik and Sterba 2015). In the afforested mangroves of the Adyar Estuary, we used the slope value (the self-thinning exponent) for the biomass–density relationship as an indicator of self-thinning. A steeper slope corresponds to increased self-thinning or decreased self-tolerance, and vice versa (Ge et al. 2017).

All statistical analyses were performed using the Paleontological Statistics (PAST) ver. 4.03 software package (Hammer et al. 2001).

Results

Extent and species composition

The mangrove cover in the Adyar Estuary and Creek was mapped at 56.6 acres, representing 15.8% of the total area (358 acres). This includes both the afforested mangroves and remnants of the pre-existing mangrove cover in the estuary. These mangroves include six species: *Aegiceras corniculatum, Avicennia marina, Avicennia officinalis, Bruguiera cylindrica*, *Excoecaria agallocha* and *Rhizophora mucronata,* with *A. marina* being the dominant species (Table 1). The discrepancy in IVI values for *A. marina* among the three stations (station 2, station 8 and station 9) was attributed to variations in the ecological parameters used to calculate IVI—relative density, relative frequency, and relative dominance. This occurred despite the higher number of quadrats studied in station 2 (11 quadrats) compared to station 8 (seven quadrats) and station 9 (five quadrats). At station 2, *A. marina* exhibited lower values for relative frequency (29.63%), relative dominance (33.65%), and relative density (25.81%), resulting in an IVI of 89.09 (Table 1). In contrast, at station 8, the species demonstrated higher values for these parameters – relative frequency (63.64%), relative dominance (64.55%), and relative density (50.00%) – which led to an IVI of 178.19 (Table 1). Similarly, station 9 showed even greater values, with relative frequency (71.43%), relative dominance (86.43%), and relative density (86.36%), contributing to the highest IVI of 244.23 (Table 1). These differences indicated that *A. marina* was more abundant, evenly distributed, and ecologically dominant at station 8 and 9 compared to station 2, reflecting variations in its ecological influence across the stations.

Structural features

The overall median tree density for the afforested mangroves was determined to be 3900 trees ha^{-1}. The highest median tree density was observed at station 7 (9300 trees ha^{-1}, Table 3), which featured 6-year-old mangrove stands dominated by *E. agallocha* species (Table 1). Tree density varied significantly among the stations ($\chi^2=24.17$, $p < 0.01$). The overall stand basal area was found to be 28.48 m^2 ha^{-1} (range: 7.37 to 144.41 m^2 ha^{-1}, Table 3). Station 6, with mixed-age mangrove stands dominated by *A. marina* (IVI: 208.27), had the highest median basal area (74.13 m^2 ha^{-1}; Table 1, Table 3). Significant differences in the distribution of tree basal area were found between the stations ($\chi^2=32.01$, $p < 0.01$).

Tree biomass

The afforested mangroves were estimated to have median AGB and BGB of 151.85 Mg ha^{-1} and 73.42 Mg ha^{-1}, respectively, and a median total vegetation biomass of 222.26 Mg ha^{-1} (Table 3). *Avicennia marina* contributed the most to the biomass aspects (80 to 83%), followed by *E. agallocha* (16 to 19%), while contributions from the other four species were negligible (< 1.0%). All biomass variables, including AGB ($\chi^2=30.92$, $p < 0.01$), BGB ($\chi^2=31.02$, $p < 0.01$), and total vegetation biomass ($\chi^2=30.32$, $p < 0.01$), varied significantly among the stations. The station with the oldest mangrove stands (22-year-old), station 5, dominated by *A. marina* trees (IVI: 266.66, Table 1) had the highest AGB (676.86 Mg ha^{-1}), BGB (238.48 Mg ha^{-1}), and total vegetation biomass (915.34 Mg ha^{-1}) of any station (Table 3).

Vegetation carbon storage

The afforested mangroves were estimated to have an above-ground, below-ground, and total mangrove vegetation carbon stock of 72.89 Mg C ha^{-1}, 28.63 Mg C ha^{-1}, and 99.89 Mg C ha^{-1}, respectively (Table 3). The total mangrove vegetation carbon stock was found to sequester an equivalent of 366.60 Mg CO_2e ha^{-1}. The total carbon storage and CO_2 sequestration potential in the estuary were calculated as 2288.00 Mg C and 8397.05 Mg CO_2e, respectively, based on the total area of afforested mangroves (56.6 acres). Carbon and CO_2e were primarily sequestered by *A. marina* stands, followed by *E. agallocha* stands, while the other four species sequestered less CO_2. The Kruskal–Wallis test revealed significant differences ($p < 0.01$) among the stations in terms of above-ground, below-ground, and total mangrove vegetation carbon stocks and their corresponding CO_2e sequestration. The oldest mangrove stands at station 5 exhibited higher median values for all carbon stocks (Table 3).

Annual accumulation rate of biomass and vegetation carbon

The afforested mangroves exhibited an annual accumulation rate of total vegetation biomass at 31.53 Mg ha^{-1} year^{-1}. The mangrove vegetation biomass was found to sequester 14.22

Table 3. Vegetation structure and carbon storage potential of the afforested mangroves in the Adyar Estuary, Chennai. Values are median (minimum–maximum). Abbreviations: BA = basal area, AGB = above-ground vegetation biomass, BGB = below-ground vegetation biomass, TB = total vegetation biomass, AGVC = above-ground vegetation carbon, BGVC = below-ground vegetation carbon, TVC = total vegetation carbon; $TVCO_2e$ = total vegetation CO_2 equivalent.

Station	Density (ha^{-1})	BA ($m^2\ ha^{-1}$)	AGB ($Mg\ ha^{-1}$)	BGB ($Mg\ ha^{-1}$)	TB ($Mg\ ha^{-1}$)	AGVC ($Mg\ C\ ha^{-1}$)	BGVC ($Mg\ C\ ha^{-1}$)	TVC ($Mg\ C\ ha^{-1}$)	$TVCO_2e$ ($Mg\ CO_2e\ ha^{-1}$)	Annual TB accumulation rate ($Mg\ ha^{-1}\ year^{-1}$)	Annual TVC sequestration rate ($Mg\ C\ ha^{-1}\ year^{-1}$)	Annual $TVCO_2e$ sequestration rate ($Mg\ CO_2e\ ha^{-1}\ year^{-1}$)
Station 1	2650 (2300–3000)	14.81 (11.00–18.62)	63.38 (63.11–63.65)	31.06 (29.74–32.39)	94.44 (92.85–96.03)	30.42 (30.29–30.55)	12.11 (11.60–12.63)	42.54 (41.89–43.18)	156.11 (153.74–158.47)	15.74 (15.47–16.01)	7.09 (6.98–7.20)	26.02 (25.62–26.41)
Station 2	2800 (1700–5100)	17.66 (7.37–31.55)	74.20 (31.91–137.05)	36.83 (16.63–67.47)	111.02 (48.54–204.52)	35.61 (15.32–65.78)	14.36 (6.49–26.31)	49.98 (21.80–92.10)	183.41 (80.02–337.99)	18.50 (8.09–34.09)	8.33 (3.63–15.35)	30.57 (13.34–56.33)
Station 3	5600 (5400–5800)	27.86 (27.57–28.14)	89.04 (87.27–90.80)	46.95 (46.25–47.64)	135.98 (133.52–138.45)	42.74 (41.89–43.59)	18.31 (18.04–18.58)	61.05 (59.93–62.17)	224.04 (219.93 – 228.15)	22.66 (22.25–23.07)	10.17 (9.99–10.36)	37.34 (36.66–38.03)
Station 4	2650 (2200–3900)	24.54 (10.24–42.31)	179.86 (60.60–334.54)	76.67 (28.95–137.52)	256.53 (89.55–472.07)	86.33 (29.09–160.58)	29.90 (11.29–53.63)	116.23 (40.38–214.21)	426.58 (148.19–786.17)	18.32 (6.40–33.72)	8.30 (2.88–15.30)	30.47 (10.58–56.15)
Station 5	4200 (1300–6900)	69.25 (53.04–132.78)	676.86 (396.76–1020.46)	238.48 (170.42–426.26)	915.34 (567.18–1446.72)	324.89 (190.44–489.82)	93.01 (66.46–166.24)	417.90 (256.91–656.06)	1533.70 (942.85–2407.75)	41.61 (25.78–65.76)	19.00 (11.68–29.82)	69.71 (42.86–109.44)
Station 6	6300 (3900–10000)	74.13 (28.48–144.41)	297.89 (146.77–1168.45)	133.29 (75.49–474.79)	429.01 (222.26–1643.24)	142.99 (70.45–560.85)	51.98 (29.44–185.17)	194.12 (99.89–746.02)	712.43 (366.60–2737.90)	67.48 (37.04–96.66)	30.39 (16.65–43.88)	111.54 (61.1–161.05)
Station 7	9300 (5100–11700)	39.51 (32.71–49.39)	164.07 (100.91–323.13)	86.87 (54.31–121.46)	250.95 (155.23–444.59)	78.75 (48.44–155.10)	33.88 (21.18–47.37)	112.64 (69.62–202.47)	413.37 (255.51–743.08)	41.82 (25.87–74.10)	18.77 (11.60–33.75)	68.90 (42.58–123.85)
Station 8	4700 (1900–5900)	28.19 (17.53–98.51)	136.70 (66.10–782.12)	66.09 (34.12–317.86)	204.90 (100.22–1099.98)	65.62 (31.73–375.42)	25.78 (13.31–123.97)	92.21 (45.03–499.38)	338.42 (165.27–1832.74)	34.15 (16.70–183.33)	15.37 (7.51–83.23)	56.40 (27.54–305.46)
Station 9	3500 (2300–11800)	36.27 (26.13–44.34)	241.16 (118.22–304.67)	106.75 (55.61–132.54)	347.92 (173.83–437.21)	115.76 (56.74–146.24)	41.63 (21.69–51.69)	157.39 (78.43–197.93)	577.63 (287.85–726.41)	57.99 (28.97–72.87)	26.23 (13.07–32.99)	96.27 (47.97–121.07)
Overall estuary	3900 (1300–11800)	28.48 (7.37–144.41)	151.85 (31.91–1168.45)	73.42 (16.63–474.79)	222.26 (48.54–1643.24)	72.89 (15.32–560.85)	28.63 (6.49–185.17)	99.89 (21.80–746.02)	366.60 (80.02–2737.9)	31.53 (6.40–183.33)	14.22 (2.88–83.23)	52.19 (10.58–305.46)

$Mg\ C\ ha^{-1}\ year^{-1}$ of carbon and 52.19 $Mg\ CO_2e\ ha^{-1}\ year^{-1}$ (Table 3). Considering the total extent of afforested mangroves (56.6 acres), the annual sequestration of total vegetation carbon and CO_2 equivalent in the estuary was calculated to be 325.71 $Mg\ C\ year^{-1}$ and 1195.42 $Mg\ CO_2e\ year^{-1}$, respectively. For annual accumulation rates, the Kruskal–Wallis test revealed significant differences ($p < 0.01$) among the stations. Station 6, characterized by mixed-age mangrove stands dominated by *Avicennia marina* (IVI: 208.27), showed the highest median annual accumulation rates (Table 3).

Size distribution of trees

Overall, the estuary's afforested mangroves predominantly consisted of narrow-sized trees (median DBH: 8.27 cm), which is expected as most of the stations studied comprised 6-year-old mangrove stands. In the estuary, the majority (67.1%) of trees had a diameter of less than 10 cm (Fig. 2). Stations dominated by young mangroves (6-year-old) – stations 1, 2, 3, 7, 8 and 9 – exhibited a skewed distribution of narrow trees. In contrast, stations with older mangroves (station 4 and 5) displayed a mix of both narrow and large trees (Fig. 2). The tree size distribution at the mixed-age mangrove station (station 6) was comparable to that observed in stations with 6-year-old stands (Fig. 2).

Relationship between tree diameter, height, density and biomass

Tree height was positively correlated with the tree DBH of the mangrove stands across all stations and the estuary as a whole (Fig. 3), indicating that tree height increases with expanding DBH. In the estuary, the overall median mangrove tree height was 4.20 m. It was observed that as the density of mangrove trees increased, the individual tree biomass (above-ground, below-ground and total biomass) decreased (Fig. 4). The slopes (−0.57 for AGB versus density, −0.51 for BGB versus density, and −0.55 for total tree biomass versus density) were relatively shallow, suggesting a reduced self-thinning effect or enhanced self-tolerance among the afforested mangroves in the estuary.

Discussion

Mangrove extent

A comparison of the pre-existing mangrove extent (118.6 acres, Selvam et al. 1991) with the current mangrove cover (56.6 acres) indicates that 47.7% of the original mangrove cover has been retained or restored in the study area. This underscores the success of the conservation and restoration efforts in the region.

Structural development – tree density and basal area

Of the six afforested mangrove species, *Avicennia marina* and *Excoecaria agallocha* were found to be dominant species

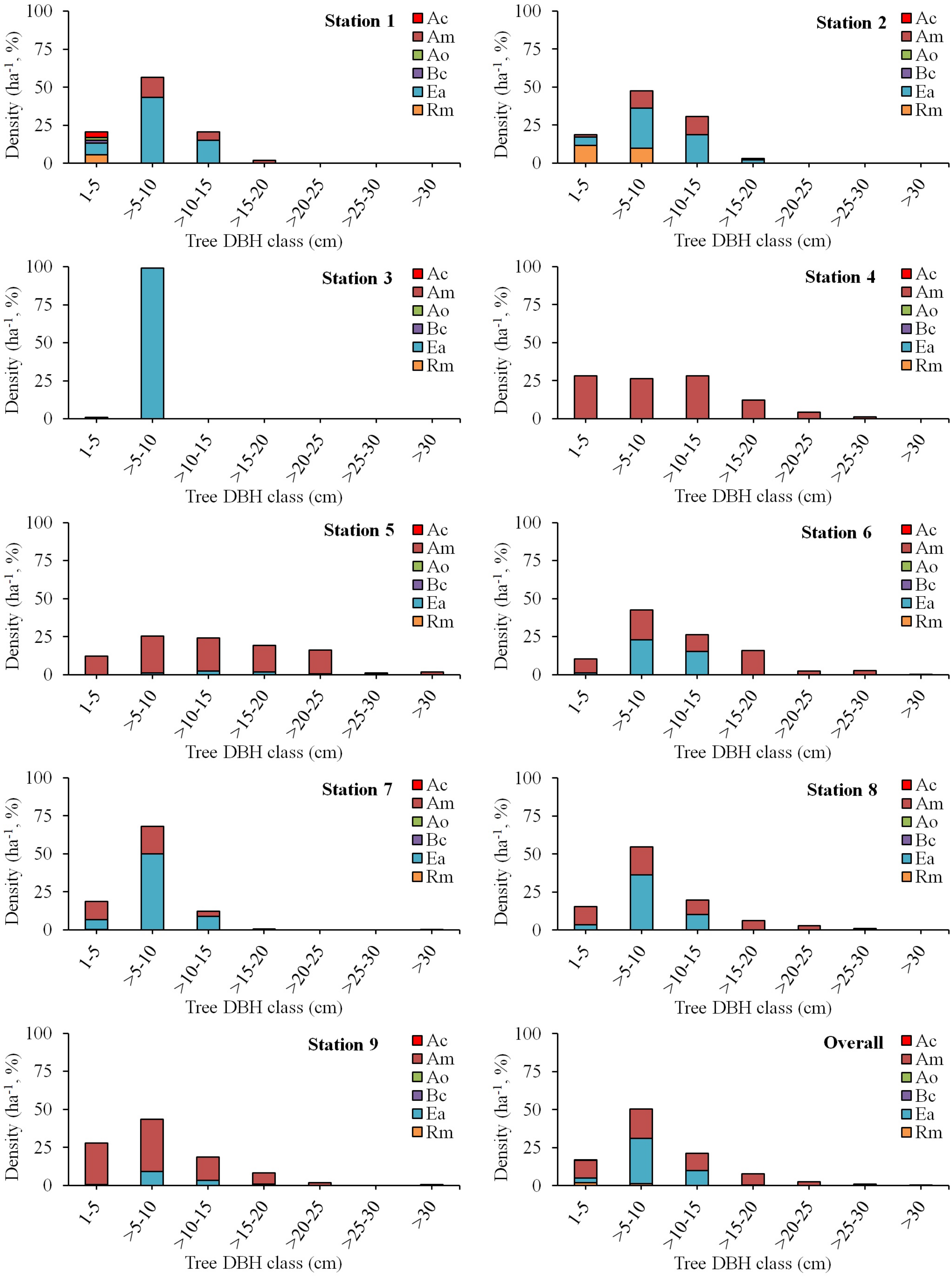

Figure 2. Station wise distribution of tree diameter classes for afforested mangroves in Adyar Estuary, Chennai (Bar colors represent mangrove species. See Table 1 for species abbreviations).

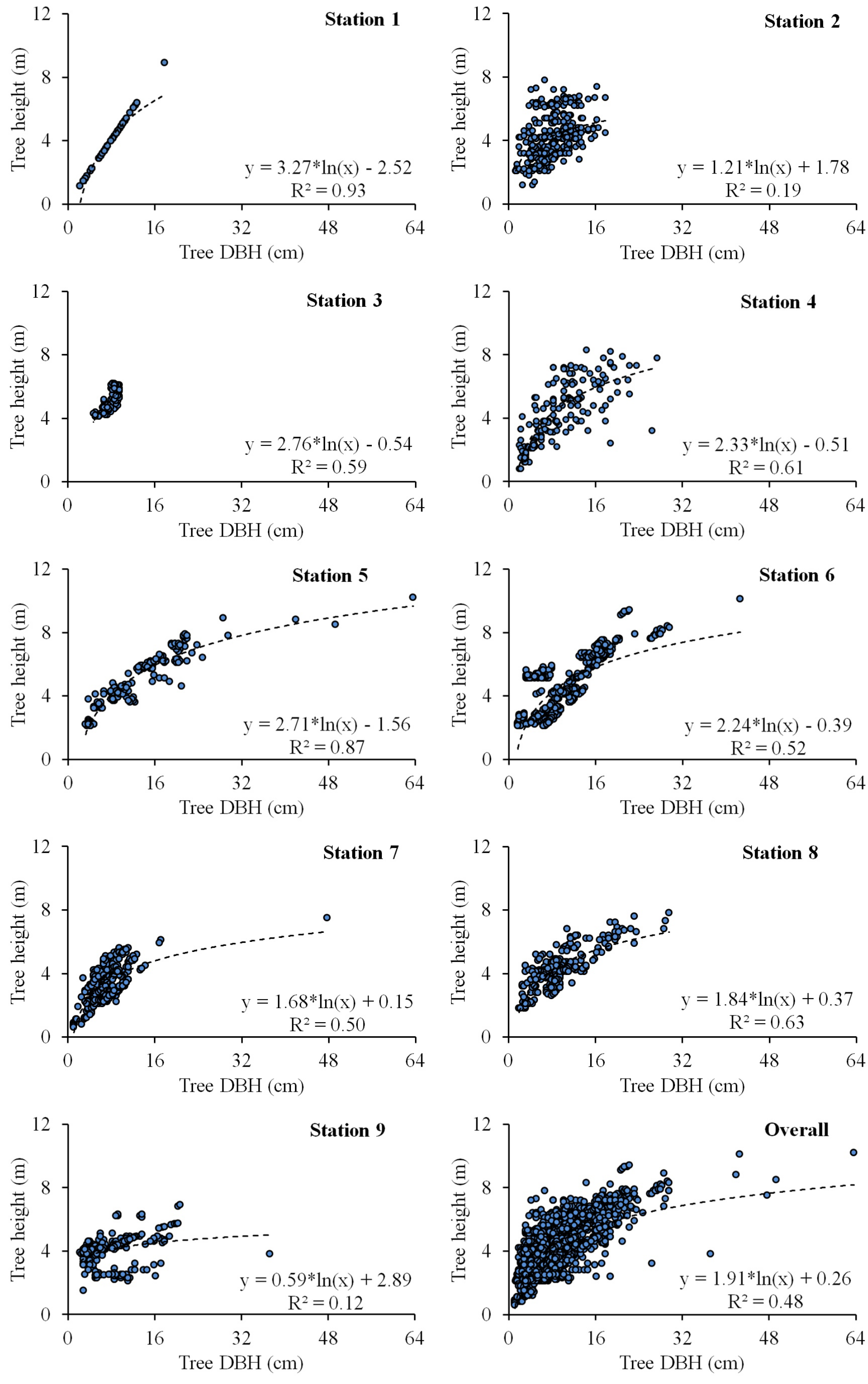

Figure 3. Station wise diameter–height relationship for afforested mangroves in Adyar Estuary, Chennai.

in the estuary. High densities of these two species aligned with their differing tolerance levels under natural conditions (Alongi 2009). For instance, *A. marina*, with its high salinity tolerance and adaptability to thrive across low, mid and high intertidal zones (Clough 1992), exhibited high densities when planted behind *R. mucronata*, which was established near the water front. Conversely, *E. agallocha*, although less tolerant to salinity, demonstrated high densities due to its ability to survive in mid to high intertidal zones (Clough 1992), thriving when planted in the interior parts of the estuary. *Avicennia*

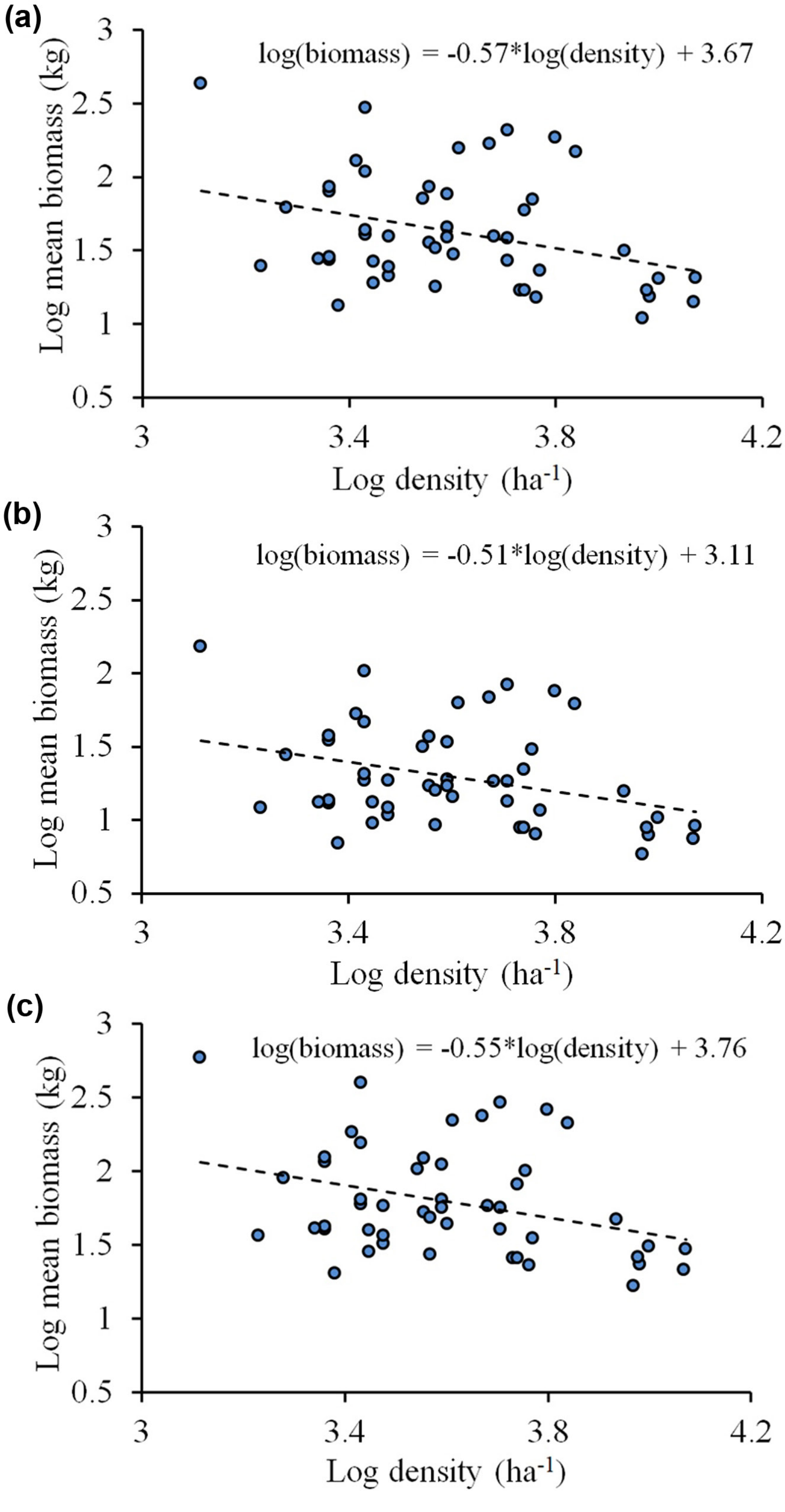

Figure 4. Relationship between tree density and (a) above-ground biomass, (b) below-ground biomass and (c) total tree biomass in the afforested mangroves of Adyar Estuary, Chennai.

marina, E. agallocha and *Sonneratia apetala* were reported to be found in the pre-existing natural mangroves of the estuary (Selvam et al. 1991). However, during this survey, *S. apetala* was not recorded. This absence could be attributed to its historically low density (only three plants ha^{-1} with an IVI of 26.94, Selvam et al. 1991), making it susceptible to localized extirpation, as well as significant environmental changes over time, including alterations in salinity and hydrological regimes, or the impact of anthropogenic activities. Increased salinity stress resulting from reduced freshwater input has adversely affected the growth of *S. apetala* in the Sundarbans (Rahman et al. 2020). Potential shifts in habitat conditions might have contributed to its absence in our findings, underscoring the importance of long-term ecological monitoring to assess changes in mangrove biodiversity. The IVI values in the present study showed that other species, such as *Rhizophora mucronata, Aegiceras corniculatum, Avicennia officinalis* and *Bruguiera cylindrica,* used for plantations, were only detected as minor contingents. Furthermore, *A. marina* and *E. agallocha* are less sensitive to pollution than other mangrove species (MacFarlane et al. 2003, Hossain et al. 2022). This suggests that careful species selection should be made in mangrove restoration, taking into account species that can adapt to the specific environmental conditions of a given area (Devaney et al. 2021). Restoration efforts in the estuary prioritized native mangrove species, avoiding non-native species introduction, ensuring no adverse impact on native biodiversity. However, the exclusion of *S. apetala*, a historically present species, highlights the need for species-specific considerations in restoration strategies. Integrating historically present species into restoration efforts is crucial for restoring ecological balance, promoting long-term biodiversity, and enhancing ecosystem health.

The observed median mangrove tree density (3900 trees ha^{-1}) indicates very dense mangrove distribution (> 1500 trees ha^{-1}) (Mursalim et al. 2020) in the estuary. Such high densities of mangroves can be attributed to the favorable tidal fluctuations, freshwater supply and protection of mangroves in the Adyar Estuary. In general, the density of mangroves was found to be influenced by the hydrology and sediment characteristics of the local environment. Although the freshwater supply to the mangroves in the estuary is limited, the mangroves are able to withstand these conditions through their own structural adaptations. Additionally, the mortality of afforested mangrove plants was minimal in this area. The CRRT's initiative to replant saplings lost during the 2015 floods in Chennai, in particular, can be credited with the low mortality rate (Padmanabhan 2019). Multiple replanting, rather than single planting, is a typical mitigation strategy for minimizing seedling mortality and achieving high mangrove densities (Friess 2017). The afforested mangroves' median basal area of 28.48 m^2 ha^{-1} further demonstrated their good condition, as pristine mangroves typically exhibit a basal area of over 25 m^2 ha^{-1} (George et al. 2019). Furthermore, the median tree density of the estuary's afforested mangroves was relatively higher than that of the pre-existing natural mangroves (144 ha^{-1}) (Selvam et al. 1991). This comparison shows that the afforested mangroves in the estuary have grown and established well. However, other parameters such as tree DBH (67.10% of trees under 10 cm DBH) and tree height (4.20 m) were found to be relatively low in the afforested mangroves despite the higher tree density (3900 trees ha^{-1}) compared to the natural mangroves. The historical natural mangroves of the estuary were reported to have a significant proportion of trees with DBH between 20 and 40 cm and a mean height ranging from 14.40 to 21.30 m (Selvam et al. 1991). Considering that restored mangroves take nearly 40 years to achieve the same biomass as intact mangroves (Azman et al. 2021), the afforested mangroves in the Adyar Estuary still require ongoing monitoring and conservation, as they have not yet reached the biomass levels of the pre-existing natural mangrove forests.

Structural development – biomass and vegetation carbon storage

Many factors influence mangrove biomass, including tree density, species composition, growth forms, tree height, stem diameter, age of the mangroves, climate, management regime, proximity to water channels and sediment nutrients (Harishma et al. 2020). The above-ground, below-ground and total vegetation biomasses of Adyar afforested mangroves were found to be higher than those of the afforested mangroves in the Mahanadi mangrove wetland (Sahu et al. 2016) and the Vellar–Coleroon estuarine complex (Kandasamy et al. 2021). Mangrove plantations in the Adyar Estuary ranged in age from 6 to 21 years, which could account for the significant biomass accumulation. In contrast, the Mahanadi mangrove plantations (Sahu et al. 2016) were 15 years old, and the planted mangroves in the Vellar–Coleroon estuarine complex (Kandasamy et al. 2021) were 16 to 27 years old. Biomass components of mangroves are significantly impacted by factors such as increased salinity and nutrient enrichment. For instance, increasing salinity increases the BGB more than the AGB, even if nutrient enrichment promotes the AGB more (Ragavan et al. 2021a). According to Komiyama et al. (2019), mangroves in tropical monsoon climates experience considerable seasonal fluctuations in soil salinity, with salinity resembling freshwater during the monsoon and seawater during the summer. Enhanced stem expansion during the rainy season is shown to be caused by a combination of lower soil water salinity and high nutrient levels, compared to the dry season. This demonstrates how the structure and function of tropical mangroves are significantly impacted by the dynamic environment, particularly periodic variations in soil water salinity and nutrient status.

Less self-thinning indicates higher site quality in terms of productivity, soil fertility and water availability (Ge et al. 2017). Therefore, the shallower slope of the density–biomass relationship in the current study, which suggests less self-thinning, implies higher site quality in the Adyar Estuary. The estuary sustains afforested mangroves despite the pollution (Rubalingeswari et al. 2021) caused by the increasing discharge of industrial and domestic effluents from Chennai. One possible explanation is that mangroves have a relatively high tolerance to pollution, rather than being adversely affected by the more obvious stressors, such as changes in hydrology and land use (Yan et al. 2017). Another possibility is that the mangroves extract nutrients from pollution and store them to prevent nutrient deficiency in saline conditions, thereby supporting better physiological activity.

Vegetation carbon storage

The estimated total vegetation carbon storage and CO_2 equivalent sequestration in the Adyar Estuary afforested mangroves were greater than those in the Mahanadi mangrove wetland mangrove plantations (Sahu et al. 2016) and the Vellar–Coleroon estuarine complex mangrove plantations (Kandasamy et al. 2021). These discrepancies in carbon sequestration potential could be explained by variations in species composition and the age of mangrove stands. Considering *Avicennia marina,* which dominates the afforested mangroves in Adyar, Mahanadi and Vellar–Coleroon, their carbon storage capacities are similar. The fact that the older mangrove stands in the study – 22 years old – display the highest amount of vegetation carbon storage confirms that age is a key factor in increased biomass accumulation and, consequently, greater carbon storage capacity (Alongi 2012, 2020). Further, the high growth efficiency and biomass production of *A. marina* contribute to its superior carbon sequestration rate compared to *R. mucronata* stands (Kathiresan et al. 2013). Additionally, *A. marina* consistently exhibits the highest CO_2 assimilation rates and stomatal conductance among mangrove species in the study area (Clough and Sim 1989, Alongi 2009), further enhancing its potential for photosynthetic carbon fixation. The relatively higher salinity tolerance of *A. marina* allows the species to thrive under diverse conditions, resulting in widespread presence in nearly all studied stations. The findings suggest that the substantial carbon and CO_2e sequestration observed in *A. marina* stands in this study can be attributed to factors such as stand age, high photosynthetic efficiency, and salinity tolerance.

According to a recent estimate, the global median mangrove carbon reserve in AGB is 94.10 Mg C ha^{-1} and in BGB, it is 34.1 Mg C ha^{-1} (Alongi 2020). By demonstrating 72.89 Mg C ha^{-1} and 28.63 Mg C ha^{-1} in above- and belowground mangrove vegetation components, respectively, the afforested mangroves in the Adyar Estuary showed similar carbon stocks. The Adyar afforested mangroves had an annual biomass accumulation rate of 31.53 Mg ha^{-1} $year^{-1}$ and a carbon sequestration rate of 14.22 Mg C ha^{-1} $year^{-1}$, which were comparable to other restored or recovered mangroves. For instance, a 23-year-old naturally restored mangroves in the Philippines, following an earthquake, shows a carbon sequestration rate of 4.32 Mg C ha^{-1} $year^{-1}$ through vegetation biomass components (Salmo et al. 2019). Similar results were found in Malaysia, where replanting mangroves resulted in a vegetation carbon sequestration rate of 4.40 Mg C ha^{-1} $year^{-1}$ in the first 12 years, which then decreased to less than 1.0 Mg C ha^{-1} $year^{-1}$ after 62 years (Adame et al. 2018). This implies that the high carbon sequestration rate in the Adyar Estuary may be due to the stand's relatively younger age (predominantly 6-year-old stands). It is anticipated that biomass and carbon sequestration rates will decline in the future as the mangrove stands reach maturity and sediment accretion slows (Salmo et al. 2019). This pattern is validated in an Indian mangrove plantation, where vegetation carbon sequestration was 0.98 Mg C ha^{-1} $year^{-1}$ for *A. marina* stands aged 16 to 27.2 years (average: 22.5 years) (Kandasamy et al. 2021). The smallest carbon reserves are found in isolated stands in the dry tropics and immature plantation forests. However, these areas continue to accumulate carbon as they age, at least up to 66 years (Alongi 2020), highlighting the importance of their conservation.

Restored ecological functions

Afforestation or rehabilitation may not exactly replace a habitat; however, habitat offsets can restore a certain degree of ecosystem services (Friess 2017). The afforested mangroves of the Adyar Estuary can be inferred to provide a variety of ecological services (Fig. 5), although they have not been restored to the pre-existing natural mangroves.

As an ecological infrastructure, mangroves can serve as natural buffers against extreme weather events and catastrophes (Gómez-Baggethun et al. 2013, van der Meulen et al. 2023). For instance, in 2004, mangroves in the Cuddalore district of Tamil Nadu, India, reduced the impact of waves caused by the tsunami and protected the coastline (Danielsen et al. 2005). The afforested mangroves of the Adyar Estuary can provide protective buffers for local communities and infrastructure, especially in the Coastal Regulation Zone-II regions surrounding the Adyar Estuary and Creek (Fig. 5). The high density of mangrove trees may also provide additional strength by reflecting and dissipating highly energetic flows from natural disasters (Mukherjee et al. 2022).

Mangroves are blue carbon ecosystem with the highest capacity to store carbon per unit of area compared to other ecosystems such as salt marshes and seagrasses (Raw et al. 2023). Mangroves have gained global attention for their conservation, management, and restoration, particularly due to their role in ecosystem-based adaptation (EbA) for nations implementing climate change adaptation and mitigation strategies (Kauffman et al. 2020). In this context, carbon sequestration by the afforested mangroves in the estuary (Fig. 5) highlights their contribution to the coast's climate change resilience, as well as to India's Intended Nationally Determined Contribution under the Paris Agreement.

In the Adyar Estuary, mullets (1.5 to 4.2 tons $year^{-1}$) and prawns (2.1 to 3.8 tons $year^{-1}$) are the main contributors to the estuarine fisheries output (Datta 2011). The presence of afforested mangroves could support greater biodiversity in the estuary (Fig. 5). A study on the ichthyofaunal diversity following the eco-restoration project revealed the presence of 28 fish species, compared to just four species in the Adyar Eco Park, which was previously environmentally degraded (Ramanujam et al. 2014). Additionally, the creation of the Eco Park has led to an increase in the populations of birds, animals, amphibians and reptiles (CRC 2019). The mangroves in the Eco Park and the estuary are also educationally valuable as they serve as a focal point for interactive learning, providing formal or informal education and training for environmental enthusiasts, children, and the general public through the celebration of environmental-related events and

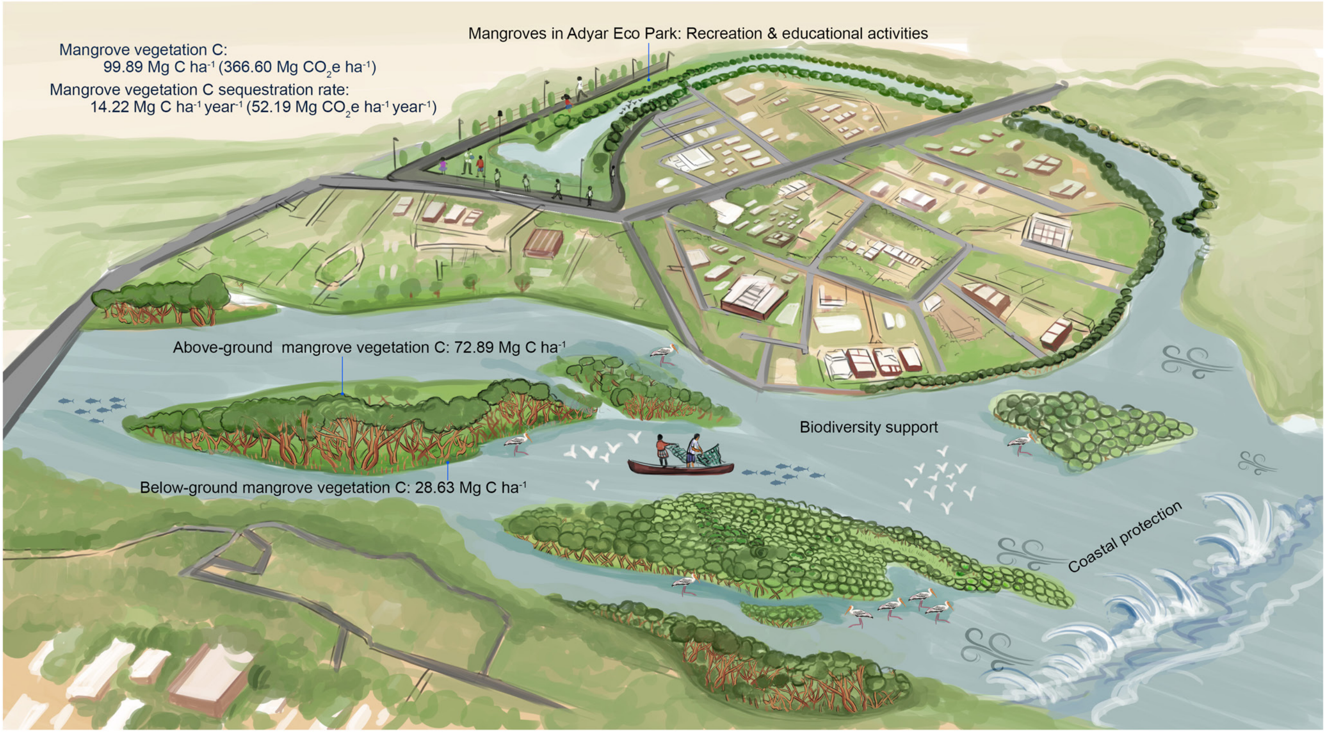

Figure 5. Illustration showing ecological significance of afforested mangroves in Adyar Estuary, Chennai (C denotes carbon).

awareness campaigns (CRRT 2019a, Mariappan and Acharya 2020). This location has been used for recreational physical activity, relaxation, and ecotourism activities (CRRT 2019b). All of this enhances access to the cultural services offered by these afforested mangroves (Fig. 5). Moreover, the mangrove plantations and continuous monitoring in the estuary would provide direct, indirect, and induced jobs in the short term, as indicated by global-level nature-based recovery projects (Raes et al. 2021), thereby offering socio-economic value.

Factors responsible for the afforested mangroves establishment

The success of mangrove restoration is measured using indicators such as vegetation development, floristic succession and the restoration of ecosystem functions and services (Pham et al. 2017, Cadier et al. 2020). In this study, the tree density indicates significantly greater structural development compared to the density of pre-existing natural mangroves. Furthermore, it is evident that the afforested mangroves have reestablished some ecological services. The successful establishment of these mangroves is reflected in both their structural characteristics and the restored ecological benefits in the Adyar Estuary. Successful mangrove rehabilitation requires the application of ecologically appropriate rehabilitation principles (Friess 2017). These principles include understanding the ecology of local mangrove species and hydrological patterns, eliminating factors that hinder seedling establishment, designing suitable rehabilitation sites, and conducting active plantation efforts to achieve the set goals (Lewis 2005).

The eco-restoration of mangroves in the estuary involved interventions based on ecological restoration concepts (Adyar Poonga Trust 2008). These interventions included the following:

1) recognizing the characteristics of the mangrove ecosystem and rebuilding the environment to function as the preferred ecosystem (a process achieved by using locally adapted mangrove species);
2) minimizing external influences on the site (a process achieved through land reclamation from garbage and debris dumping);
3) constantly addressing residual external pressures (a process achieved through multiple replanting efforts to offset sapling losses);
4) providing funding and resources to maintain the area (a process achieved through continuous monitoring); and
5) establishing long-term engagement between the site and the people (a process achieved through community participation in design, project execution and use).

All these initiatives contributed to the success of the eco-restoration efforts.

Implications

Even though technical guidelines are available, knowledge transfer between mangrove restoration projects remains insufficient (Ellison et al. 2020). Therefore, regions experiencing mangrove degradation or possessing potential areas for mangrove afforestation could benefit from the knowledge gained from the Adyar Estuary mangrove eco-restoration efforts. Due to disturbances, mangroves can release stored carbon in the biomass, near-surface, and deep sediments at levels three to five times higher than those of tropical forest emissions (Pendleton et al. 2012). Coastal erosion, tree mortality, natural disaster damage, deforestation, illegal logging, conversion to aquaculture, cattle pastures, agriculture and other land-use changes are various forms of disturbances (Alongi 2020). Therefore, any disturbances to afforested mangroves in the Adyar Estuary could potentially lead to greenhouse gas emissions, which should be prevented through the enforcement of protective measures. Furthermore, mangrove restoration in other critical coastal ecosystems, such as mudflats, should be avoided, as it leads to ecosystem conversion rather than true restoration.

Conclusion

This study underscores the importance of mangrove restoration and afforestation in coastal environments, emphasizing the need to follow ecological restoration principles. Mangrove afforestation can significantly contribute to environmental sustainability. In India, mangrove afforestation typically involves the costly and labor-intensive process of planting seedlings or saplings. However, successful restoration requires addressing the factors that prevent or delay natural colonization. Creating favorable hydrological conditions and eliminating stressors are crucial for this process. Many restoration sites in India suffer from poor structural characteristics due to unscientific site and species selection, inappropriate planting techniques, hydrological alterations, and a lack of post-planting monitoring. These shortcomings hinder the full ecological function of mangroves. Moreover, planting monospecific or non-native species can negatively impact ecosystem function. We recommend focusing on hydrologically favorable degraded mangrove areas and abandoned aquaculture ponds for mangrove afforestation, using a mix of native and locally adaptive species to ensure ecological success.

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Author contributions

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Data availability statement

Data are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.51c59zwjz (Viswanathan et al. 2025).

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