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Carbon Sequestration: A Comprehensive Study of Mangrove Ecosystems in Navi Mumbai, Maharashtra

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Abstract: *Mangrove ecosystems represent one of the most carbon-rich biomes globally, storing significantly more carbon per unit area than terrestrial forests. This study investigates carbon sequestration potential in plants, with specific emphasis on mangrove forests in Navi Mumbai, Maharashtra, India. The research synthesizes data from recent studies (2014-2025) on carbon stocks, sequestration rates, and storage mechanisms in mangrove ecosystems. Mangroves in the Thane Creek and coastal regions of Navi Mumbai, dominated by Avicennia marina, demonstrate substantial carbon storage capacity, with total carbon stocks ranging from 34.15 to 39.72 t ha^{-1}. Soil organic carbon (SOC) comprises approximately 70-89% of total ecosystem carbon, highlighting the critical role of sediments in long-term carbon storage. The study examines allometric methods, remote sensing techniques, and soil carbon analysis approaches used for biomass and carbon estimation. Key findings indicate that mangrove ecosystems sequester carbon at rates of 168-180 g C m^{-2} yr^{-1}, substantially higher than terrestrial forests. However, anthropogenic pressures including urbanization, land conversion, and developmental projects threaten these vital blue carbon ecosystems. The research underscores the urgent need for conservation and restoration of mangrove forests in Navi Mumbai as a nature-based solution for climate change mitigation while providing co-benefits of coastal protection, biodiversity conservation, and livelihood support.*

Keywords: Mangroves, Carbon sequestration, Blue carbon, Soil organic carbon, Climate change mitigation, Navi Mumbai

I. INTRODUCTION

Climate change poses unprecedented challenges to global ecosystems and human societies. The atmospheric concentration of carbon dioxide (CO_2) has increased from pre-industrial levels of 280 ppm to over 420 ppm in 2025, primarily due to fossil fuel combustion and land-use changes. Carbon sequestration is a process of capturing and storing atmospheric CO_2 by plants. This concept has emerged as a critical strategy for climate change mitigation. Among natural ecosystems, coastal blue carbon habitats, particularly mangrove forests, have gained recognition for their exceptional carbon storage and sequestration capabilities.

1.1 Carbon Sequestration in Plants

Plants sequester atmospheric carbon through photosynthesis, converting CO_2 into organic matter stored in biomass (leaves, stems, roots) and soil. Terrestrial forests store approximately 45% of terrestrial carbon, while coastal wetlands, despite covering less than 1% of Earth's surface, contribute disproportionately to global carbon cycling. The efficiency of carbon sequestration varies significantly across ecosystems, influenced by productivity, decomposition rates, and environmental conditions.

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1.2 Mangroves as Blue Carbon Ecosystems

Mangrove forests are salt-tolerant woody plants found in tropical and subtropical intertidal zones. Globally, mangroves cover approximately 137,000-152,000 km², with India hosting about 4,975 km² of mangrove cover. These ecosystems are characterized by unique adaptations including pneumatophores (aerial roots), vivipary (embryo development on parent plant), and salt excretion mechanisms, enabling survival in anaerobic, saline conditions.

Mangroves rank among the most carbon-rich forests in the tropics, with mean carbon stocks of 738.9-1023 Mg C ha^{-1} (Donato et al., 2011; Alongi, 2020). This exceptional carbon density results from: (1) high primary productivity, (2) extensive belowground biomass, (3) accumulation of organic-rich sediments in anoxic conditions that slow decomposition, and (4) tidal inputs of organic matter. Approximately 70-89% of total mangrove carbon is stored in soils at depths of 0.5-3 meters, providing long-term carbon sequestration potential (Alongi, 2014).

1.3 Mangroves in Maharashtra and Navi Mumbai

Maharashtra's coastline spans 720 km along the Arabian Sea, supporting approximately 222 km² of mangrove cover across five coastal districts: Mumbai, Thane, Raigad, Ratnagiri, and Sindhudurg. The Mumbai Metropolitan Region, including Navi Mumbai (19°03′41″N, 73°01′35″E), harbours critical mangrove ecosystems in estuaries and creeks. Thane Creek, designated as a Ramsar site in 2024, represents the largest mangrove area in the region, dominated by *Avicennia marina* with associated species including *Avicenniaofficinalis*, *Sonneratiaalba*, *Rhizophoramucronata*, and *Ceriopstagal*.

However, rapid urbanization threatens these ecosystems. Between 1990-2001, Mumbai's suburban region lost 36.54 km² (39.32%) of mangrove cover (Vijay et.al., 2005). Recent infrastructure projects, including Navi Mumbai International Airport, coastal roads, and the Mumbai-Ahmedabad bullet train, have resulted in clearance of thousands of mangrove trees. This habitat loss not only releases stored carbon but also diminishes future sequestration capacity and coastal protection services.

1.4 Research Objectives

This study aims to: (1) review carbon sequestration mechanisms in plants with emphasis on mangrove ecosystems, (2) synthesize published data on carbon stocks and sequestration rates in mangroves of Navi Mumbai and Maharashtra, (3) evaluate methodologies for biomass and carbon estimation, and (4) assess conservation implications for blue carbon management in the region.

II. MATERIALS AND METHODS

2.1 Study Area

The study focuses on mangrove ecosystems in Navi Mumbai (latitude 18°52′-19°19′N; longitude 72°51′-73°01′E), Maharashtra, India. Navi Mumbai is a planned satellite city on the western coast of India, situated across Thane Creek from Mumbai. The region experiences a tropical monsoon climate with average annual rainfall of 2,050 mm, concentrated during June-September. Mean temperatures range from 24°C (January) to 33°C (May).

Mangrove habitats in the study area occur along Thane Creek, Gorai Creek, and coastal zones of Vashi, Nerul, Belapur, Kharghar, Ulwe, and Panvel. These intertidal ecosystems are characterized by mudflats with fine sediments (>70% silt and clay content), tidal amplitude of 2-4 meters, and salinity ranging from 15-35 ppt. The dominant mangrove species is *Avicennia marina*, comprising >50% of stand composition, with associated species including *Avicenniaofficinalis*, *Sonneratia alba*, *Sonneratiaapetala*, *Rhizophoramucronata*, *Rhizophoraapiculata*, *Bruguieracylindrica*, *Ceriopstagal*, and *Acanthus ilicifolius*.

2.2 Literature Review and Data Synthesis

This study employed a systematic literature review approach, focusing on peer-reviewed publications from 2014-2025 related to carbon sequestration in mangrove ecosystems. Search databases included Google Scholar, Web of Science, Scopus, and ResearchGate using keywords: 'mangrove carbon', 'blue carbon', 'carbon sequestration', 'Navi Mumbai', 'Thane Creek', 'Maharashtra', 'Avicennia marina', and 'soil organic carbon'. Inclusion criteria prioritized: (1) studies on Indian mangroves, particularly Maharashtra; (2) research on carbon stocks, biomass, and sequestration rates; (3) methodological papers on allometric equations and carbon estimation; and (4) highly cited global reviews on mangrove blue carbon.

2.3 Carbon Stock Estimation Methods

Carbon stocks in mangrove ecosystems comprise multiple pools: aboveground biomass (stems, branches, leaves), belowground biomass (roots), pneumatophores, litter, and soil organic carbon. Published studies from the region employed three primary methodological approaches:

2.3.1 Allometric Equations: Aboveground biomass (AGB) estimation using diameter at breast height (DBH, 1.3 m) and species-specific or generalized allometric equations. Common equations include those developed by Komiyama et al. (2005) and Chave et al. (2005), incorporating wood density (ρ) and tree height (H): $AGB = \rho \times \exp(-1.349 + 1.980 \ln(DBH) + 0.207 \ln(H) - 0.0281[\ln(H)]^2)$. Belowground biomass typically estimated as 40-50% of AGB for mangrove species.

2.3.2 Remote Sensing Integration: Satellite imagery (Landsat, Sentinel, high-resolution Pléiades) combined with ground-truth data for landscape-scale carbon mapping. Normalized Difference Vegetation Index (NDVI) correlated with field-measured biomass to extrapolate carbon stocks. Studies by Patil et al. (2014) demonstrated $R^2 = 0.964$ between allometric and remote sensing approaches in Thane Creek.

2.3.3 Soil Carbon Analysis: Sediment core collection to 1-3 m depth, with laboratory analysis of: (a) soil bulk density ($g\ cm^{-3}$), (b) total organic carbon (TOC) via CHN elemental analysis or loss-on-ignition, and (c) carbon accumulation rates using radiometric dating (^{210}Pb, ^{137}Cs). Carbon stocks calculated as: SOC ($Mg\ C\ ha^{-1}$) = Σ [bulk density × TOC concentration × depth × 10,000 m^2/ha].

III. RESULTS AND DISCUSSION

3.1 Carbon Stocks in General Plant Systems

Terrestrial plant ecosystems exhibit considerable variation in carbon storage capacity (Table 1). Tropical rainforests store 120-400 $Mg\ C\ ha^{-1}$, temperate forests 60-230 $Mg\ C\ ha^{-1}$, and grasslands 200-400 $Mg\ C\ ha^{-1}$ (primarily soil). In contrast, wetland ecosystems, particularly mangroves and peatlands, demonstrate exceptional carbon densities due to waterlogged, anoxic conditions that limit organic matter decomposition.

Ecosystem Type	Carbon Stock ($Mg\ C\ ha^{-1}$)	Primary Storage Pool
Tropicalrainforests	120-400	Biomass (50-60%)
Temperate forests	60-230	Biomass & Soil
Grasslands	200-400	Soil (70-90%)
Mangroves	**738-1023**	Soil (70-89%)
Peatlands	400-1200	Peat soil (>95%)

Table 1. Carbon storage capacity across major terrestrial and coastal ecosystems. Data compiled from Donato et al. (2011), Alongi (2014), and global forest carbon reviews.

3.2 Mangrove Species Composition in Navi Mumbai

Field surveys conducted between 2017-2024 documented 8-12 mangrove species across Navi Mumbai's coastal zones (Table 2). Avicennia marina dominates with relative abundance of 13.44-39.27%, particularly in disturbed and partially protected habitats. Species composition varies with tidal positioning, substrate type, and anthropogenic disturbance.

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Upper intertidal zones support A. marina and A. officinalis, mid-zones harbor*Sonneratiaalba* and *Rhizophora* species, while lower zones feature *Ceriopstagal* and *Bruguieracylindrica*.

Species	Family	Dominance
Avicennia marina	Avicenniaceae	**Dominant**
Avicenniaofficinalis	Avicenniaceae	Co-dominant
Sonneratia alba	Lythraceae	Common
Rhizophoramucronata	Rhizophoraceae	Common
Ceriopstagal	Rhizophoraceae	Moderate
Excoecariaagallocha	Euphorbiaceae	Rare

Table 2. Major mangrove species recorded in Navi Mumbai and Thane Creek. Based on field surveys from Gorai Creek and Thane Creek mangrove ecosystems (2017-2024).

3.3 Carbon Stocks in Thane Creek Mangroves

Comprehensive carbon stock assessments in Thane Creek, the primary mangrove habitat in Navi Mumbai, reveal substantial carbon storage (Table 3). Patil et al. (2014) reported total carbon stocks of 34.15 t ha^{-1} using integrated allometry-GIS approaches, while subsequent studies employing remote sensing calibration estimated 39.72 t ha^{-1}. These values represent conservative estimates, focusing primarily on aboveground components and upper soil horizons (0-30 cm).

Location	Tree Density (ha^{-1})	AGB (t ha^{-1})	Total C Stock (t ha^{-1})
Thane Creek (average)	1726-4523	10.15-18.4	34.15-39.72
Mankhurd	High (young stands)	8.2-12.5	28.5-35.2
Vashi	Low (mature stands)	15.8-22.3	42.1-48.7
Raigad District	Variable	12.4-18.9	SOC: 17.15%

Table 3. Carbon stocks in mangrove ecosystems of Navi Mumbai and adjacent regions. AGB = Aboveground biomass; SOC = Soil organic carbon. Data compiled from Patil et al. (2014), Thane Creek studies (2023), and Raigad systematic assessment.

3.4 Soil Organic Carbon Dynamics

Soil organic carbon constitutes the largest carbon pool in mangrove ecosystems, accounting for 70-89% of total ecosystem carbon. In Raigad district mangroves (adjacent to Navi Mumbai), soil carbon concentrations reached 17.15% in Avicennia marina-dominated areas compared to 4.52% in non-mangrove zones, representing a 3.8-fold enhancement. This exceptional soil carbon accumulation results from:

(1) High sedimentation rates: Mangrove root systems trap suspended sediments and particulate organic matter. Recent studies show sedimentation rates of 0.30-0.85 cm yr^{-1} in intact mangroves, accelerated by anthropogenic watershed erosion and aquaculture runoff (Yang, 2017).

(2) Anoxic preservation: Waterlogged, anaerobic sediments inhibit microbial decomposition of organic matter. Redox potential (Eh) values of -150 to -300 mV in mangrove soils limit aerobic respiration, enhancing carbon preservation (Macreadie et al., 2015).

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(3) Autochthonous and allochthonous inputs: Mangrove-derived organic carbon (autochthonous) from root turnover, leaf litter, and woody debris combines with terrestrial runoff and marine particulate organic carbon (allochthonous) transported by tidal exchange. Stable isotope studies indicate mangrove-derived carbon contributes 49-62% of total soil organic carbon in estuarine settings.

(4) Mineral-organic associations: Fine-grained sediments (silt and clay > 70%) with high surface area facilitate mineral-organic interactions. Iron-bound and calcium-bound carbon fractions enhance SOC stability, protecting organic matter from microbial degradation for centuries to millennia.

3.5 Carbon Sequestration Rates

Global mangrove carbon sequestration rates average 168-180 g C m^{-2} yr^{-1} (1.68-1.80 Mg C ha^{-1} yr^{-1}), approximately 2-4 times higher than terrestrial forests (Alongi, 2014; Breithaupt et al., 2012). This rate encompasses both biomass accumulation and sediment carbon burial. For Indian mangroves, limited radiometric dating studies suggest comparable or slightly lower rates due to anthropogenic disturbances and sediment quality variation.

Carbon accumulation rates exhibit spatial heterogeneity based on: (1) Geomorphic setting-estuarine mangroves receive higher terrestrial carbon inputs than marine mangroves; (2) Vegetation structure-mature forests with higher biomass turnover contribute more root-derived carbon; (3) Hydroperiod-tidal amplitude and inundation frequency affect sediment deposition and organic matter export; (4) Human impacts-eutrophication and watershed degradation can paradoxically increase sedimentation rates while altering carbon quality and stability.

3.6 Anthropogenic Threats and Carbon Loss

Mangrove deforestation in Navi Mumbai represents a significant carbon loss pathway. The clearance of 36.54 km^2 (39.32%) of mangroves in Mumbai's suburban region between 1990-2001 released an estimated 26,900-37,400 Mg CO_2-equivalent, assuming average carbon stocks of 738 Mg C ha^{-1} and complete oxidation upon conversion. Recent infrastructure development continues this trend-construction of Navi Mumbai International Airport required clearing thousands of mangrove trees, while the Mumbai-Ahmedabad bullet train project approved removal of 32,044 mangroves.

Carbon emissions from mangrove conversion exceed those from terrestrial deforestation due to: (1) Higher carbon density per unit area; (2) Soil carbon oxidation-exposure of anoxic sediments to aerobic conditions accelerates decomposition, releasing centuries of accumulated carbon; (3) Permanent inundation-some converted sites become open water, eliminating future sequestration capacity; (4) Erosion-loss of root stabilization leads to sediment export, mobilizing stored carbon.

Additional stressors include pollution (microplastics in Thane Creek documented at highest levels nationally), altered hydrology from coastal engineering, invasive species, and climate change impacts (sea level rise, intensified cyclones, altered precipitation patterns).

3.7 Conservation and Restoration Strategies

Maharashtra's Mangrove Cell, established in 2012, represents a pioneering state-level conservation initiative. The Cell has protected over 15,000 ha of mangroves through: (1) Legal protection-Coastal Regulation Zone (CRZ) notifications prohibiting development within 50-100 m of mangrove boundaries; (2) Restoration programs-planting of native species (primarily Avicennia and Rhizophora) in degraded sites; (3) Community engagement-participatory management with fishing communities; (4) Research partnerships-collaboration with academic institutions for monitoring and assessment.

India's first mangrove blue carbon project was notified in 2024 under the Verified Carbon Standard (VCS) for Thane Creek. This initiative seeks to: (1) Quantify baseline carbon stocks and sequestration rates; (2) Monitor restoration outcomes; (3) Generate verified carbon credits for climate finance; (4) Demonstrate economic viability of mangrove conservation. However, challenges remain regarding: (a) Baseline establishment-distinguishing natural recovery from

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restoration impacts; (b) Permanence-ensuring protection beyond project duration; (c) Leakage-preventing displacement of development pressures to unprotected sites; (d) Co-benefits-quantifying and monetizing ecosystem services beyond carbon.

Compensatory afforestation policies mandating 5:1 replacement ratios for cleared mangroves face biological constraints. Young planted mangroves require 15-40 years to achieve carbon sequestration rates comparable to mature forests. Moreover, plantation survival rates average 40-60% due to hydrological mismatch, inadequate substrate preparation, and lack of follow-up maintenance. Thus, preservation of existing mangroves must take precedence over restoration as a climate mitigation strategy.

IV. CONCLUSION

Mangrove ecosystems in Navi Mumbai, Maharashtra, represent critical blue carbon repositories, storing 34-40 t C ha^{-1} with the majority (70-89%) sequestered in soil organic matter. These systems sequester atmospheric carbon at rates 2-4 times higher than terrestrial forests, providing substantial climate mitigation potential. The dominant species *Avicennia marina* demonstrates remarkable adaptability to disturbed environments while maintaining significant carbon storage capacity.

However, rapid urbanization threatens these ecosystems. Loss of 39% of mangrove cover in two decades represents not only immediate carbon emissions but also permanent reduction in sequestration capacity. The contrast between carbon stocks in mangrove zones (17.15% soil organic carbon) versus non-mangrove areas (4.52%) underscores the irreplaceable nature of these ecosystems.

Effective conservation requires: (1) Strict enforcement of CRZ regulations prohibiting mangrove conversion; (2) Ecosystem-based adaptation strategies integrating mangroves into coastal planning; (3) Blue carbon financing mechanisms that monetize ecosystem services; (4) Restoration prioritizing hydrologically suitable sites with native species; (5) Long-term monitoring of carbon stocks and sequestration rates to validate conservation outcomes; (6) Community participation ensuring livelihood compatibility with conservation goals.

The mangroves of Navi Mumbai exemplify the global challenge of balancing development aspirations with climate imperatives. As India pursues carbon neutrality targets, preservation and restoration of coastal blue carbon ecosystems must be prioritized. The exceptional carbon storage capacity of mangroves-exceeding that of Amazon rainforests per unit area-positions these ecosystems at the forefront of nature-based climate solutions. The time for decisive action is now, before these irreplaceable carbon reservoirs are permanently lost to development.

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