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Blue Carbon in Bangladesh: A Review of Mangrove Conservation, Carbon Sequestration, Coastal Resilience and Management Challenges

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Abstract

Blue carbon ecosystems mangroves, salt marshes, and seagrasses are examples of ecosystems that capture and store carbon in coastal and marine environments, aiding with climate change mitigation. Because of the deltaic topography and coastline's fragility, Bangladesh faces an overwhelming socioeconomic paradox which can be attempted to be overcome using blue carbon capture technologies. This paper examines the role that blue carbon ecosystems play in fostering climate resilience and biodiversity in the country and concurrently supporting emission reduction obligations nationally and globally. The article describes the existing ecological scenario and the carbon capture potential within the scope of anthropogenic pressures and climate stressors and vulnerabilities. Moreover, the research evaluates the current policies and proposes more dynamic integrated frameworks aimed at enhancing the coastal ecosystems' capacity for long-term carbon storage. With the possibility of acting as a blueprint for climate resilience adaptability, Bangladesh's coastal low-lying regions positioned them as prime candidates for blue carbon initiatives.

Keywords: Carbon sequestration, Blue carbon, Coastal Ecosystems, Mangrove Restoration, Soil Organic Carbon (SOC), Climate Change, Climate Resilience, Biodiversity.

1.Introduction

Blue carbon ecosystems along the coast, or mangroves, salt marshes, and seagrass meadows, are among the most efficient natural blue carbon ecosystems that can sequester carbon longterm, with the ability to store carbon at significantly higher rates than terrestrial forests[1]. For Bangladesh, situated at the confluence of large river systems and with more than 710 km of coastline, these ecosystems are not only crucial for climate change mitigation but also for biodiversity conservation, fish productivity, and the livelihood

security of millions of people in low-lying coastal areas[2]. These beneficial ecosystems are, nonetheless, coming under serious and intensifying degradation.

Unplanned shrimp farming, land transformation, increased salinity intrusion, and extreme weather events—exacerbated by sea-level rise—have caused extensive damage and fragmentation of blue carbon ecosystems in Bangladesh[3].

In the Sundarbans region alone, studies estimate that mangrove health has declined significantly due to altered hydrology and human pressures[4]. Similarly seagrass beds and salt marshes along the southeast coast and Saint Martin's Island are deteriorating through eutrophication, sedimentation, and disturbance from tourism activities[5]. If unabated, such environmental degradation will not only make coastal communities increasingly exposed to storm surges and erosion but also unleash enormous quantities of previously sequestered carbon, essentially canceling out the climate mitigation function of these ecosystems[6].

Baseline data on ecosystem status and carbon loss is valuable for assessing environmental deterioration. A baseline serves as a reference for assessing present and future changes, aiding scientists and decision-makers in evaluating degradation and the effects of restoration or management efforts. Indicators for these objectives include ACD, SOC, various metrics for NPP and land utilization, along with remote sensing technologies[7]. Indicators allow for the recognition of changes across various natural and degraded landscape classes and assess ecological integrity. Effective practice involves utilizing reference conditions, employing various indicators, and integrating remote sensing with field surveys[8]. Baselines with time indicators, such as pre-disturbance or prior points, enable the observation of trends in degradation and the assessment of ecosystem recovery potential. In contrast, individual indicators cannot be adapted to various ecological contexts, and the accessibility and quality of the relevant data present significant challenges for developing countries[9].

Bangladesh coast is battling with the climate change, natural hazards, and livelihood vulnerability with the partnership between NGOs and the Government. Government response invests in policy-based and infrastructural adaptation, while NGOs look at community-based resilience, sustainably using and protecting resources, and disaster planning[10]. The Coastal Embankment Project (CEP) shields the people who inhabit the coast against the floods and the tidal surge. NGOs help in the reduction of disaster risks through the use of early warnings, evacuation, and post-disaster recovery. They implemented livelihood development programs for the districts of Khulna and Satkhira, but research finds that some of the programs would expose the vulnerable people more if the design is not for the marginalized people[11]. Natural resource co-management projects like the Community-Based Fisheries Management help preserve the fisheries, wetlands, and the coastal forest.

This is an integration based on ecological and human benefits and ecological functioning. Indicators are offered in biophysical, social, and economic domains in ecological provision, anthropomic input, demand and use, instrumental and relational value, and benefit-relevant indicators like EESVs and ESPI[12]. These enable coordinated tracking that look at the ends most valued by man. This is an integrating tracking system that enables adaptive management and informed policy making so the ecosystems remain resilient[13].

In spite of increasing awareness, ongoing coastal restoration in Bangladesh is still fragmented and frequently not harmonized with blue carbon finance or with strong ecological monitoring systems. Local involvement, indigenous knowledge, or long-term ecosystem management approaches that can be scaled up are seldom integrated into most projects[14] . Moreover, a lack of large-scale carbon stock estimations and restoration-based carbon accounting has so far deprived the country of tapping global climate finance streams like carbon offset markets and REDD+ mechanisms [15] .

This study addresses these issues of immediate importance by investigating site-specific blue carbon restoration measures in three priority coastal locations: the Dacope and Shyamnagar locations in Khulna-Satkhira districts, Cox's Bazar and Teknaf in the southeast region, and Saint Martin's Island in the Bay of Bengal. These locations experience various degrees of ecosystem degradation and potential for restoration. The project centers on a combination of nature-based solutions like mangrove and seagrass restoration, salt marsh recovery, and biochar application, integrated with community-based adaptation and participatory resource management. Through this, the study aims to enhance ecosystem services, increase carbon storage, and open opportunities for community resilience and engagement in climate finance.

2.Literature Review

2.1 Global Overview of Blue Carbon Ecosystems

Blue carbon is the carbon sequestered and stored by seagrasses, mangroves, and tidal salt marshes, which are marine and coastal ecosystems. Not only are these some of the most productive biomes on the planet, but they also play a disproportionate role in the global carbon cycle. According to the seminal UNEP report by Nellemann et al. (2009), blue carbon habitats can sequester carbon at rates up to 10 times higher than terrestrial forests on a per-area basis and store it in long-lived sediment pools, making them critical tools in the fight against climate change[16] .

Blue carbon ecosystems—such as mangroves, tidal marshes, and seagrass meadows—perform dual climate-regulating functions. They actively remove atmospheric CO₂ through

photosynthesis and sequester it in below-ground biomass and anaerobic sediments, where the carbon can remain stored for centuries to millennia without oxidizing[17] . This long-term storage is significantly more stable than many terrestrial systems due to reduced decomposition rates under waterlogged, oxygen-poor conditions. However, when these ecosystems are degraded through deforestation, dredging, or land conversion, the stored carbon is re-released into the atmosphere as CO₂ or methane, effectively turning these carbon sinks into net sources of greenhouse gas emissions[18]. Due to this, restoration and conservation of blue carbon ecosystems is critical not just to climate mitigation—by means of carbon drawdown—but also to adaptation, since they shield the shoreline from storms and sea level rise .

Globally, the integration of blue carbon into national climate strategies is gaining momentum. Countries like Indonesia, Australia, and the Philippines have launched pioneering programs that incorporate coastal ecosystems into greenhouse gas (GHG) inventories, Nationally Determined Contributions (NDCs), and voluntary carbon markets[19] . These efforts combine mangrove reforestation, carbon accounting methodologies, and community-based conservation financing to mobilize climate funds and enhance ecosystem services. For example, Indonesia's Blue Carbon Strategy involves ecosystem mapping, carbon stock measurement, and policy to link restoration activities with carbon crediting under REDD+ schemes[20] .

2.2 State of Blue Carbon Research in Bangladesh

In South Asia, blue carbon assets remain significantly underutilized. Bangladesh, lying in the middle of the Ganges-Brahmaputra-Meghna (GBM) Delta, holds considerable blue carbon assets waiting to be tapped into. The Sundarbans, being the largest uninterrupted mangrove forest in the world and a UNESCO World Heritage site, spreads over 6,000 km² and holds considerable carbon sequestration capacity, with estimates close to 1,000 Mg C/ha in sediment reservoirs alone[21]. Additionally, it is an important source for preserving biodiversity and reducing disaster risk and is used as a cyclone and storm surge protective barrier from millions of inhabitants. Greater blue carbon research efforts, blue carbon-based restoration processes, and blue carbon-based climate financing within Bangladesh could greatly increase national resilience while aiding international emission reduction targets as well.

Estimates by Ahmed et al. (2019) suggest that the Sundarbans mangrove forest stores over 56 million tonnes of organic carbon, highlighting its central role in both regional climate regulation and ecosystem service provision. This makes the Sundarbans one of the largest natural carbon reservoirs in South Asia. However, the breadth of blue carbon research in Bangladesh remains narrow, with the overwhelming majority of studies focusing on mangrove ecosystems, while salt marshes and seagrass meadows remain critically underexplored. Although patches of seagrass have been observed in areas such as Saint Martin's Island, Teknaf Peninsula, and Cox's Bazar, there is a clear absence of systematic

ecological mapping, biomass quantification, or long-term restoration strategies for these habitats[22] . This gap significantly limits the country's ability to include the full scope of coastal carbon sinks in its national carbon accounting frameworks.

Simultaneously, anthropogenic pressures take the form of illegal removal of timber, overexploitation, aquaculture conversion, and direct input of agricultural and industrial pollutants into water bodies, and are causing degradation in these ecosystems[23] . Additionally, these pressures are exacerbated by climatic stresses like cyclones, storm surges, increasing sea level, and intrusion of saline water into blue carbon ecosystems further compromising their structural and functional capacity. These disturbances reduce blue carbon ecosystems' capacity for carbon storage and threaten coastal communities depending on blue carbon ecosystems for fisheries products, fuelwood, and increasing ability to withstand storms.

2.3 Blue Carbon and Coastal Resilience

The ecosystem's resilience—i.e. an ecosystem's capacity to resist disturbance with little change in its fundamental structure and function—is increasingly recognized as a keystone of sustainable blue carbon management[24] . Restoring mangrove, salt marsh, and seagrass meadows has been shown to enhance carbon sequestration, sedimentation, shoreline stabilization, nutrient cycling, and biodiversity, including fisheries recruitment[25] . These cobenefits twin showcase the worth of investing in nature-based solutions that combine climate mitigation, disaster risk reduction, and livelihood promotion—a combination highly critical in risk-prone deltaic regions like Bangladesh.

In Bangladesh, mangrove replanting and afforestation initiatives—overwhelmingly under the control of the Bangladesh Forest Department—have been conducted for decades along the exposed coastal fringes of Noakhali, Patuakhali, Barguna, and Khulna. They were implemented to combat coastal erosion and contribute towards carbon sequestration. However, their outcomes have been uneven due to a variety of outstanding problems. One of the significant issues is the biased selection of mangrove species, often leading to the preferential selection of fast-growing or monoculture species like *Sonneratia apetala* at the expense of ecologically native and resilient species like *Avicennia* or *Rhizophora*[26] . Additionally, there are weak monitoring systems with little post-planting checking of survival, biodiversity improvements, or carbon sequestration.

Restoration efforts have similarly concentrated on plant density rather than ecological process, resulting in dense but unsustainable regimes vulnerable to disease, windthrow, and poor faunal diversity. This has necessitated a shift to adaptive, ecosystem-based restoration centered on species diversity, hydrological restoration, natural regeneration, and most

importantly, community engagement. Throughout the globe and also in Bangladesh, locally driven approaches—where locals are trained, empowered, and financially motivated—have reported enhanced success rates in restoration time, socio-economic benefits, and governance effectiveness [28].

2.4 Community, Equity, and Justice in Blue Carbon Initiatives

It is important to recognize that blue carbon ecosystem restoration is inherently bound up with coastal communities that depend upon, live within, and interact with those ecosystems (Figure 5). Examples from countries as diverse as Indonesia, Kenya, and Micronesia show that effective integration of community-based restoration schemes with existing initiatives for raising awareness, offering economic incentives (e.g., payments for environmental services), and providing secure tenure rights produces significantly better results. These improvements include higher success rates in vegetation cover regeneration, a reduction in destructive practices including over-harvesting and trawling, and higher incomes for households due to livelihood diversification. In Bangladesh's context, this implies likely benefits from pursuing a co-management approach incorporating ecologically sustainable goals into the socio-economic structures of coastal communities and hence promoting simultaneously human well-being and environmentally sound stewardship. IN Bangladesh coastal communities are regularly subject to increased vulnerability while serving as environmental guardians themselves. They greatly rely upon mangroves, tidal wetlands, and estuarine ecosystems' services—their fisheries, fuelwood, aquaculture, and cyclone and storm protection—for their economic livelihoods[29] . However, they are among the most vulnerable populations to climatic events and associated hazards including cyclones, salinity intrusion, and erosion.

This dual dependence highlights the need for people-focused blue carbon approaches. There is a need for participatory planning processes, benefit-sharing arrangements, and capacitybuilding programs to install local stakeholders as empowered custodians and hence ensure blue carbon initiatives to be equitable and sustainable [30]. Co-management approaches based on communities being both beneficiaries and active custodian's integral to management processes have shown promise in enhancing conservation success and building up socioeconomic resilience.

2.5 Threats and Risks Highlighted in Literature

Concurrently, the anthropogenic stresses equate in terms of unauthorized cutting down of woods, over-exploitation, converting for aquaculture use, and direct discharge of agricultural and industrial effluents into the habitats, and causing degradation within the latter. Besides this, the pressures are further amplified by climatic stresses such as cyclones,

storm tides, increase in the height of the seas, and inflow of saline waters into the blue carbon habitats further degrading the structure and functional integrity thereof.

They reduce the stored carbon capability of the blue carbon ecosystems and threaten the people at the coasts who depend upon the blue carbon ecosystems for fisheries products, fuelwood, and increasing resilience for coping with storms. While replanting is an anchor activity, the recent innovation hints at the direction for the future of bioengineering applications for sequestration of carbon in the soil, immobilization of sediments, and accelerating ecological restoration.

While traditional replanting remains an anchor measure, more recent advances lean toward the opportunities for bioengineering interventions to sequester carbon in the ground, immobilize sediments, and accelerate ecological recovery. One technology that holds great promise is biochar, a stable carbon material that is produced by pyrolysis (pyrolytic treatment of organic biomass in low oxygen conditions). Applied to degraded or saline coastal soils, biochar may improve porosity, microbial activity, and water retention, alongside organic carbon storage, and reduce methane (CH_4) and nitrous oxide (N_2O) emissions the latter being a principal driver of global warming[6]. Notably, biochar made from halophytes (salt-tolerant plants like *Salicornia* or *Suaeda*) has been particularly found to be efficient in improving soil fertility and resilience in high-salinity coastal environments. These bioengineering strategies offer scalable, cost-effective, and climate-tolerant alternatives to conventional reforestation, especially in data-scarce and vulnerable coastal settings like Bangladesh.

Another new blue carbon science frontier is the restoration and transplantation of seagrass meadows, which are amongst the most productive ecosystems for long-term carbon storage and for value as habitat[30]. Seagrasses have the potential to store 83,000 metric tons of carbon per square kilometer, mostly in sediments[31]. Rehabilitation techniques—i.e., rhizome transplanting, broadcasting seeding, and biodegradable coir mat or jute fabric-based sediment stabilization—have worked in countries like Australia, the Philippines, and the United States[18]. However, in Bangladesh, coordinated efforts at mapping, conserving, or rehabilitating seagrass habitats are close to nil due to the absence of available data, technical skills, and institutional concern. There are just scattered references to seagrass occurrence in Cox's Bazar and the Saint Martin's Island region, where there are high threats from tourism, overfishing, and sedimentation[32].

Technological innovation is rapidly revolutionizing the landscape of ecosystem restoration. Remote sensing, aerial mapping, and geographic information system (GIS) modeling now enable high-resolution identification of degraded habitats, spatial prioritization of restoration, and non-destructive monitoring of carbon stock change and biodiversity over time[30]. These new digital tools are particularly valuable in data-scarce locations like Bangladesh, where insitu ecological baselines are still limited. Incorporating such technology into national conservation planning—along with local ecological knowledge

(LEK)—can potentially close the science-community practice gap by offering culturally appropriate and ecologically effective interventions.

2.6 Policy and Institutional Analysis

At policy level, Bangladesh has made remarkable progress towards integrating nature-based solutions into its action plan on national climate change. Both National Adaptation Plan (NAP) and updated Nationally Determined Contributions (NDCs) recognize the substantive role played by coastal ecosystems in planning to improve resilience to climate change[10]. However, these policies suffer from a lack in offering a distinct framework for quantification, verification, and inclusion in carbon markets for blue carbon. This policy gap indicates an urgent need for interdisciplinary and research-based initiatives that integrate science inputs successfully into governance and ground-level implementation. Formulation of standardized approaches for estimating carbon stocks, guaranteeing transparency in distribution of benefits, and inclusion in national mechanisms for climate finance could significantly enhance Bangladesh's credibility and efficiency in its climate actions[11].

This study utilizes an interdisciplinary set of geospatial, analytical, community-based, and ecological approaches to elucidate comprehensively and enhance blue carbon dynamics in Bangladesh's coastal zone. These approaches have been grouped into separate foundational domains to respond to the interdisciplinary nature of the inquiry.

3. Objectives

- To assess the blue carbon sequestration potential of coastal Bangladesh's priority blue carbon ecosystems.
- To assess the ecological effectiveness of restoration efforts, such as mangrove reforestation, salt marsh restoration, and seagrass transplantation.
- To evaluate the effectiveness of biochar application as a soil amendment in ensuring longterm carbon sequestration in saline coastal soils.
- To develop a participatory project and policy-congruent a blue carbon sequestration and adaptive coastal zone management model aligned with national policy.

4: Materials and Methods

4. Review Methodology

4.1 Review Design

This study was conducted as a narrative and evidence-based review of blue carbon ecosystems in coastal Bangladesh, with particular emphasis on mangrove ecosystems, carbon sequestration, coastal resilience, conservation, restoration, policy, and research gaps. The review synthesized findings from peer-reviewed scientific literature and relevant reports to evaluate the current understanding of blue carbon in Bangladesh and identify priorities for future conservation and management.

The review was designed to connect ecological evidence with coastal conservation and management needs. Particular attention was given to the Sundarbans and other coastal ecosystems, including salt marshes and seagrass habitats, where information is available.

4.2 Literature Search Strategy

Relevant literature was identified using scientific and academic sources covering blue carbon, mangrove ecosystems, coastal conservation, carbon sequestration, climate resilience, and coastal management. The literature search focused primarily on studies concerning Bangladesh and, where Bangladesh-specific evidence was limited, selected international studies were used to provide scientific context and comparative evidence.

The main search terms included combinations of the following keywords:

- * “blue carbon” AND Bangladesh
- * “blue carbon” AND Sundarbans
- * “mangrove carbon” AND Bangladesh
- * “carbon sequestration” AND mangrove
- * “soil organic carbon” AND Sundarbans
- * “coastal ecosystem” AND Bangladesh
- * “mangrove restoration” AND Bangladesh
- * “seagrass” AND Bangladesh

- * “salt marsh” AND Bangladesh
- * “coastal resilience” AND Bangladesh
- * “blue carbon conservation” AND Bangladesh
- * “nature-based solutions” AND coastal Bangladesh
- * “blue carbon policy” AND Bangladesh

The search emphasized literature addressing carbon stocks, carbon sequestration, ecosystem degradation, restoration, biodiversity, climate adaptation, community participation, policy, and climate-finance opportunities.

4.3 Literature Selection and Eligibility

Studies were selected according to their relevance to the objectives of the review. Priority was given to peer-reviewed research articles, review papers, scientific reports, and policy-related publications that provided evidence concerning blue carbon ecosystems and coastal management.

Studies were considered relevant when they addressed one or more of the following themes:

1. Blue carbon storage and sequestration;
2. Mangrove biomass and sediment carbon;
3. Sundarbans ecosystem condition and conservation;
4. Salt marsh and seagrass ecosystems;
5. Coastal degradation and environmental pressures;
6. Mangrove restoration and nature-based solutions;
7. Coastal resilience and ecosystem services;
8. Community participation and coastal resource management;
9. Climate policy, NDCs and adaptation planning; and
10. Research gaps and carbon-accounting approaches.

Studies that were not directly related to coastal blue carbon, Bangladesh, or the broader scientific context required for interpretation were given lower priority.

4.4 Data Extraction and Thematic Synthesis

Information from the selected literature was organized according to major themes relevant to blue carbon conservation in Bangladesh. The principal information extracted from each study included study location, ecosystem type, carbon pool or ecosystem service investigated, major findings, threats or management issues, and implications for conservation and restoration.

The evidence was subsequently synthesized into the following major thematic categories:

- * Blue carbon ecosystems and their ecological functions;
- * Carbon stocks and sequestration potential;
- * Sundarbans and other coastal ecosystems of Bangladesh;
- * Major anthropogenic and climatic threats;
- * Coastal resilience and ecosystem services;
- * Conservation and restoration approaches;
- * Community participation and socioeconomic considerations;
- * Policy and institutional frameworks;
- * Carbon accounting and climate-finance opportunities; and
- * Research gaps and future priorities.

Where findings differed among studies, the differences were considered in relation to ecosystem type, study location, measurement approach, environmental conditions, and study objectives rather than treating all reported values as directly comparable.

4.5 Assessment of Carbon Sequestration Evidence

The review considered the major carbon pools associated with blue carbon ecosystems, including aboveground biomass, belowground biomass, dead organic matter, and soil or sediment organic carbon. Particular attention was given to sediment carbon because long-term carbon storage in coastal ecosystems is strongly associated with belowground and sedimentary pools.

Reported carbon-stock and sequestration estimates were interpreted according to their original study context. Values from different ecosystems, locations, depths, and measurement methods were not directly combined unless methodological comparability was established. This approach was adopted to avoid overestimating national blue carbon storage potential.

4.6 Assessment of Conservation and Restoration Approaches

Published evidence on mangrove conservation, ecological restoration, natural regeneration, community-based management, seagrass conservation, salt-marsh protection, and other nature-based approaches was reviewed to identify their potential contribution to carbon storage and coastal resilience.

The review also examined emerging approaches such as remote sensing, GIS-based monitoring, ecological restoration, and carbon-accounting systems. Biochar was considered as an emerging soil-management approach based on published evidence, rather than as an experimentally tested intervention within this review.

4.7 Policy and Management Analysis

Relevant national and international policy documents and published studies were examined to assess the extent to which blue carbon ecosystems are reflected in Bangladesh's climate adaptation, mitigation, biodiversity conservation, and coastal management frameworks.

The review considered the relationship between blue carbon conservation and national climate commitments, coastal management, nature-based solutions, community participation, and potential climate-finance mechanisms. Particular attention was given to the need for standardized carbon measurement, monitoring, reporting and verification systems.

4.8 Limitations of the Review Methodology

The available literature on blue carbon in Bangladesh is unevenly distributed among ecosystem types and geographic areas. Research on mangroves, particularly the Sundarbans, is substantially more developed than research on salt marshes and seagrass ecosystems. Differences in sampling depth, carbon-pool definitions, measurement techniques, spatial coverage, and reporting units also limit direct comparison among studies.

Therefore, this review does not attempt to produce a single national estimate of blue carbon storage from heterogeneous published values. Instead, it synthesizes available evidence, identifies areas of agreement and uncertainty, and highlights research priorities required for developing a more comprehensive national blue carbon assessment.

5. Results

The anticipated outcomes of this study are multi-dimensional, encompassing ecological restoration success, enhanced carbon sequestration, and improved community resilience. Restoration of mangroves and salt marshes is expected to enhance biodiversity, stabilize shorelines, and increase sediment trapping capacity[1, 4]. By planting native species such as *Avicennia marina*, *Rhizophora mucronata*, and *Spartina alterniflora*, we anticipate a notable increase in vegetation cover, with measurable improvements in habitat structure for wildlife, such as fish, crustaceans, and migratory birds[5, 24].

The transplantation of seagrass species such as *Halophila ovalis* is expected to improve habitat quality for marine life, particularly small fish and invertebrates, which are crucial for local fishing communities. Restoration sites will show increased underwater vegetation cover and sediment stability, promoting clearer water and enhanced biodiversity. We expect a significant increase in soil organic carbon (SOC) in both mangrove and salt marsh zones, especially in sites where biochar is applied. The biochar-amended soils should exhibit improved carbon retention, with enhanced soil fertility and microbial activity, leading to greater long-term carbon storage[7, 31]. A measurable rise in carbon stock is expected, with the potential for hundreds to thousands of tonnes of CO₂ equivalent to be sequestered annually in restored habitats. The application of biochar will improve soil structure, increase water retention in saline soils, and provide long-term stability for plant root systems[19, 25].

This will be evident through healthier vegetation, increased root biomass, and greater resistance to erosion. Monitoring of soil pH and salinity will reveal the buffering capacity

of biochar-amended soils, enhancing plant growth even in degraded coastal areas. The restoration of coastal ecosystems is expected to bolster the resilience of these habitats against storm surges, sea-level rise, and saline intrusion[24, 28, 32]. The marsh and mangrove ecosystems are expected to show enhanced sediment accretion, greater coastal protection, and greater biodiversity, and provide a more complete recovery of ecosystems after disturbances. The community-based approach is expected to instill a high level of local ownership and ensure long-term permanence[11, 21]. By involving local communities in activities leading to livelihood promotion and conservation, the project hopes to advance coastal communities' adaptive capacities while offering alternative livelihood opportunities through ecotourism, sustainable fisheries and carbon credit schemes. The implementation of livelihood approaches that integrate community-based ecotourism, sustainable fishery management, and carbon offset schemes is likely to increase local people's economic welfare. These activities will create earnings and raise awareness about the need to sustain the intactness of coastal ecosystems[14].

Soil organic carbon (SOC) content was found increasing exponentially with the 15-year restoration of the mangrove forest with 60-year-old forest sites bearing much higher SOC content. Soil salinity and pH and soil bulk density were found increasing with the finer texture within the mudflats and the planted mangrove plantation[43].

The study shows that the blue carbon content in nine sampling sites varies significantly. The highest blue carbon content is found at SC1 (375 Mg ha⁻¹), indicating a productive ecosystem dominated by mature vegetation. The lowest carbon content is found at SC9 (200 Mg ha⁻¹), indicating a loss of carbon storing capacity. The study emphasizes the importance of conserving high-carbon sites like SC1 and prioritizing lower-carbon sites for restoration and carbon enhancement[44].

Workshops and training programs will result in a more informed and skilled local workforce, capable of managing and monitoring coastal resources. Communities will benefit from a deeper understanding of climate resilience practices and sustainable resource management.

6: Discussion

6.1 Blue Carbon Potential of Coastal Bangladesh

The reviewed literature demonstrates that Bangladesh possesses substantial blue carbon potential because of the extent and ecological importance of its coastal ecosystems. Mangrove forests, tidal wetlands, and seagrass habitats contribute to carbon sequestration while simultaneously providing important ecosystem services, including shoreline stabilization, biodiversity conservation, fisheries support, and protection from coastal hazards. The Sundarbans represents the most extensively studied blue carbon ecosystem in Bangladesh and is particularly important because carbon is stored not only in vegetation but also in belowground biomass and sediment.

Globally, mangrove ecosystems are recognized as carbon-rich forests, with a substantial proportion of their carbon stored belowground. Donato et al. (2011) demonstrated the high carbon density of tropical mangrove forests, while subsequent research has emphasized the importance of sedimentary carbon pools for long-term storage. In Bangladesh, studies of the Sundarbans have similarly identified considerable carbon storage potential. Chanda et al. (2016) assessed blue carbon stocks in the Bangladesh Sundarbans and highlighted the importance of forest condition and future ecosystem changes for determining long-term carbon storage.

The available evidence therefore indicates that the carbon value of Bangladesh's coastal ecosystems should not be assessed solely from aboveground vegetation. Soil and sediment organic carbon represent important long-term carbon reservoirs and need to be incorporated into national blue carbon assessments.

6.2 The Sundarbans as the Principal Blue Carbon Ecosystem

The Sundarbans is the dominant focus of blue carbon research in Bangladesh. Its extensive mangrove vegetation, tidal influence, high sediment deposition, and large belowground carbon pool provide important conditions for long-term carbon storage. The ecosystem also provides multiple services that extend beyond climate mitigation, including habitat for biodiversity, fisheries support, shoreline protection, and livelihood resources for coastal communities.

Research has demonstrated that carbon stocks vary spatially within mangrove ecosystems. Chanda et al. (2016), for example, reported substantial variation in blue carbon stocks among sampling locations in the Bangladesh Sundarbans. Such spatial variability indicates that carbon storage cannot be represented reliably by applying a single carbon-stock value to the entire Sundarbans.

Long-term restoration can also influence soil carbon accumulation. Evidence from mangrove chronosequence research indicates that restored mangroves can progressively develop soil organic carbon stocks over several decades. This finding supports the importance of long-term conservation and restoration rather than focusing only on short-term vegetation establishment.

6.3 Carbon Pools and Carbon Sequestration

The literature identifies several major carbon pools in coastal ecosystems: aboveground biomass, belowground biomass, dead organic matter, and soil or sediment organic carbon. Among these pools, sediment carbon is particularly important in mangrove and seagrass ecosystems because carbon can remain stored under waterlogged and oxygen-limited conditions.

Mangrove carbon cycling is strongly influenced by productivity, litter production, root accumulation, sediment deposition, decomposition, and tidal exchange. Alongi (2014) emphasized that mangrove forests function as important carbon reservoirs because substantial quantities of carbon are stored in biomass and sediments.

Seagrass ecosystems also have significant carbon-storage potential. Fourqurean et al. (2012) identified seagrass ecosystems as globally important carbon stocks, with a substantial proportion of stored carbon occurring in sediments. However, the literature reviewed for Bangladesh indicates that information on the distribution, biomass, and carbon stocks of seagrass ecosystems remains considerably more limited than information on the Sundarbans.

Consequently, Bangladesh's national blue carbon assessment should incorporate multiple carbon pools and ecosystem types rather than concentrating exclusively on mangrove aboveground biomass.

6.4 Spatial and Ecosystem-Level Differences

The reviewed studies indicate considerable spatial variation in blue carbon storage across coastal ecosystems. Differences in vegetation structure, species composition, soil texture, salinity, tidal conditions, sedimentation, disturbance history, and restoration age can influence carbon stocks.

For example, restored mangrove forests may accumulate soil carbon progressively over time, while degraded areas may experience reductions in vegetation biomass and changes in sediment conditions. Therefore, carbon estimates from one location should not automatically be generalized to all coastal areas of Bangladesh.

The same limitation applies to comparisons between mangroves, salt marshes, and seagrass ecosystems. These ecosystems differ in productivity, sediment characteristics, carbon burial processes, and spatial distribution. A national blue carbon inventory should therefore use ecosystem-specific methods and clearly distinguish among carbon pools.

6.5 Threats to Blue Carbon Storage

The literature identifies both anthropogenic and climatic pressures as major threats to blue carbon ecosystems in Bangladesh. Deforestation, unauthorized timber extraction, aquaculture expansion,

land-use conversion, pollution, and unsustainable resource use can reduce vegetation cover and disturb carbon-rich sediments.

Shrimp farming and associated land-use changes have been identified as important pressures on coastal environments. Hossain et al. (2013) documented environmental impacts associated with shrimp farming in coastal Bangladesh, while other studies have identified broader biodiversity and ecosystem-management challenges.

Climatic pressures further increase ecosystem vulnerability. Salinity intrusion, cyclones, storm surges, sea-level rise, erosion, and changing hydrological conditions can affect mangrove structure and productivity. Islam and Bhuiyan (2018) discussed the degradation pressures affecting the Sundarbans and emphasized the need for sustainable management.

These pressures have implications for both carbon storage and coastal resilience. When vegetation is degraded or carbon-rich sediments are disturbed, the ecosystem's capacity to maintain carbon storage and provide shoreline protection may decline.

6.6 Blue Carbon and Coastal Resilience

The reviewed evidence indicates that blue carbon conservation provides benefits beyond greenhouse-gas mitigation. Mangroves, salt marshes, and seagrasses can contribute to shoreline stabilization, sediment retention, biodiversity conservation, and support for fisheries.

For Bangladesh, these ecosystem functions are particularly important because coastal communities are exposed to cyclones, storm surges, erosion, and salinity intrusion. Mangrove vegetation can reduce wave energy and contribute to shoreline protection, while wetlands and seagrasses provide habitat and support coastal food webs.

Therefore, blue carbon conservation can be considered within a broader nature-based coastal management framework. The climate mitigation value of carbon storage should be assessed together with adaptation and ecosystem-service benefits rather than in isolation.

6.7 Restoration and Conservation Approaches

The literature suggests that effective coastal restoration should move beyond simple tree planting toward ecosystem-based restoration. Restoration success depends on appropriate species selection, hydrological conditions, sediment characteristics, salinity, elevation, natural regeneration, and long-term monitoring.

Bangladesh has a long history of coastal afforestation and mangrove planting. However, the reviewed literature indicates that restoration outcomes can vary according to species selection, site conditions, planting density, and post-restoration management. If restoration focuses primarily on planting numbers without considering ecological processes, vegetation establishment may not necessarily translate into long-term ecosystem recovery.

Natural regeneration and hydrological restoration are therefore important components of restoration planning. Where ecological conditions permit, allowing natural regeneration may reduce intervention requirements and support more diverse and locally appropriate vegetation communities.

Restoration should also incorporate monitoring of survival, vegetation development, biodiversity, sediment processes, and carbon accumulation. Long-term monitoring is particularly important because carbon-stock development may occur over decades rather than within a single planting season.

6.8 Seagrass and Salt Marsh Ecosystems: Research Gaps

Compared with mangroves, salt marshes and seagrass ecosystems remain poorly documented in Bangladesh. The literature identifies seagrass occurrence in areas including Saint Martin's Island, Cox's Bazar, and the southeastern coastal region, but systematic information on ecosystem extent, biomass, carbon stocks, and long-term change remains limited.

This represents an important knowledge gap because excluding these ecosystems could result in an incomplete assessment of Bangladesh's coastal carbon resources. Remote sensing, field surveys, ecological mapping, and sediment-carbon measurements could help establish more reliable baselines.

Future research should therefore expand beyond the Sundarbans and investigate the distribution, condition, carbon storage, and conservation status of non-mangrove blue carbon ecosystems.

6.9 Community Participation and Socioeconomic Dimensions

Blue carbon conservation in Bangladesh is closely connected with the livelihoods of coastal communities. Communities depend on mangrove and wetland ecosystems for fisheries, fuelwood, aquaculture, and other ecosystem services. At the same time, these communities are highly exposed to climate-related hazards.

The reviewed literature supports greater participation of local communities in coastal resource management. Participatory planning, co-management, livelihood diversification, awareness

programs, and equitable benefit-sharing can improve the social sustainability of conservation interventions.

Community involvement is therefore not simply a socioeconomic addition to blue carbon projects. It can influence the long-term effectiveness of conservation by improving local stewardship and reducing pressures on natural resources.

6.10 Remote Sensing, GIS and Carbon Monitoring

A major finding from the literature is the increasing importance of remote sensing and GIS for monitoring coastal ecosystems. Satellite imagery can support ecosystem mapping, land-cover classification, change detection, and identification of degraded areas. Pham et al. (2019) reviewed remote-sensing approaches for monitoring blue carbon ecosystems and demonstrated the potential of these technologies for large-scale assessment.

For Bangladesh, remote sensing is particularly valuable because field-based measurements across extensive and difficult-to-access coastal areas are expensive and time-consuming. However, satellite-based assessments should be combined with field observations and sediment or biomass measurements to improve validation and carbon-stock estimation.

A standardized monitoring framework integrating satellite observations, GIS, field surveys, permanent monitoring sites, and carbon measurements would strengthen the scientific basis of Bangladesh's blue carbon inventory.

6.11 Policy and Climate-Finance Implications

The reviewed literature indicates that blue carbon conservation has relevance to Bangladesh's broader climate adaptation and mitigation objectives. Existing national climate and coastal-management policies recognize the importance of ecosystem-based approaches, but a more explicit framework for blue carbon measurement, monitoring, reporting, and verification is needed.

A national blue carbon framework could help connect ecosystem conservation with climate planning, biodiversity conservation, coastal management, and potential climate-finance mechanisms. However, the development of carbon-finance opportunities requires robust carbon accounting, transparent monitoring, clear institutional responsibilities, and appropriate safeguards for local communities.

Carbon markets should therefore not be considered a substitute for ecosystem conservation. Rather, potential financial mechanisms should complement conservation, restoration, community participation, and long-term ecosystem management.

6.12 Research Gaps and Future Priorities

The synthesis identifies several major research gaps. First, Bangladesh lacks a comprehensive and standardized national inventory covering all major blue carbon ecosystems and carbon pools. Second, research is disproportionately concentrated on the Sundarbans, while salt marshes and seagrasses remain comparatively understudied.

Third, differences in sampling methods, sediment depths, carbon-pool definitions, and analytical techniques make direct comparison among existing studies difficult. Standardized protocols would improve the comparability of future measurements.

Fourth, long-term monitoring remains necessary to understand how restoration, sea-level rise, salinity, cyclones, and land-use change affect carbon stocks over time. Finally, greater integration of ecological data with socioeconomic and governance information is required to develop conservation strategies that are both scientifically effective and socially appropriate.

6.13 Overall Synthesis

Overall, the reviewed evidence indicates that Bangladesh's coastal ecosystems represent important natural carbon reservoirs and provide multiple co-benefits for coastal resilience and biodiversity. The strongest body of evidence concerns the Sundarbans, while substantial information gaps remain for seagrass and salt-marsh ecosystems.

The literature also demonstrates that blue carbon conservation should not be treated solely as a carbon-sequestration intervention. Its effectiveness depends on ecosystem condition, hydrology, sediment dynamics, biodiversity, local livelihoods, governance, and long-term monitoring.

A Bangladesh-specific blue carbon strategy should therefore integrate conservation of existing high-carbon ecosystems, ecological restoration of degraded areas, standardized carbon assessment, remote-sensing-based monitoring, community participation, and policy coordination. Such an integrated approach would provide a stronger scientific and management basis for incorporating blue carbon into Bangladesh's wider coastal conservation and climate-resilience planning.

7: Limitations and Challenges

The blue carbon initiatives of Bangladesh face various impediments that hinder effective ecosystem restoration and blue carbon sequestration. The coastal habitats experience high susceptibility to pressures of climate, such as cyclones, sea level rise, and saltwater intrusion, especially in areas like Dacope and the Sundarbans[4] [33] . Uncontrolled methods of shrimp farming and changes in land use lead to mangrove and wetland ecosystem degradation, hindering natural development processes and reducing biodiversity[2] [3] . In addition, scientific investigation and strategic planning face limitations in terms of lack of standard measurement methods for blue carbon, insufficient national statistics, and inefficient use of remote sensing and data acquisition technologies[30] . The adoption of blue carbon approaches into national climate strategies is challenged by weak governance and policy formalization, worsened by conflicting mandates of institutions[10, 11] . Local communities experience resistance based on socio-economic reliance on energy-consuming industries, while these might displace other income-generating sources[29] . Additionally, development initiatives are hindered by tenure issues of land, use of short-term financial capital, and lack of expert skills needed to perform sophisticated restoration methods, seagrass transplantation and biochar application[6, 21, 34]. Overcoming these impediments is critical to achieving the long-term sustainability of blue carbon activities of the country.

8: Future Directions

The results of this study shall serve to enable further investigation into blue carbon science and coastal planning. However, development of blue carbon programs in Bangladesh requires adopting an integrated, multidisciplinary plan of action. Key to this process is establishing national blue carbon inventories of mangroves, salt marshes, and seagrass, using standard methods and remote-sensing tools to track changes to these ecosystems[30] . In addition, blue carbon ecosystems need to be explicitly included in national mitigation and adaptation plans as defined by Bangladesh's Climate Change Strategy and Action Plan (BCCSAP) and Nationally Determined Contributions (NDCs) to mobilize international climate financing mechanisms[10, 21].

Further research is needed to assess the long-term sustainability of sequestration of carbon in restored ecosystems under climatic stresses, such as sea-level rise, saltwater intrusion, and cyclone impacts. In addition to applying ecological engineering and natural regeneration principles, this endeavor entails broadening the use of cutting-edge restoration techniques, such as applying biochar to damaged soils[6]. Strengthening local institutions and creating

replicable demonstration programs at other vulnerable coastal regions are necessary for scaling up these techniques.

9: Research Gap and Novelty of the Review

Although blue carbon has received increasing scientific attention, important knowledge and synthesis gaps remain for Bangladesh. Existing studies have contributed valuable information on mangrove carbon stocks, ecosystem degradation, coastal biodiversity, restoration, and climate adaptation. However, the available evidence is fragmented across individual ecosystems, locations, and research themes. Much of the Bangladesh-specific literature focuses on the Sundarbans, while comparatively less attention has been given to salt marshes and seagrass ecosystems and their potential contribution to the national blue carbon budget.

A second gap concerns the integration of carbon sequestration with coastal conservation and resilience. Previous research has often examined carbon storage, ecosystem degradation, restoration, or climate adaptation as separate issues. Consequently, there is limited synthesis of how blue carbon conservation can simultaneously contribute to carbon storage, biodiversity conservation, shoreline protection, ecosystem resilience, and coastal livelihoods. The literature reviewed in this study indicates that these functions are closely interconnected and should be considered within an integrated coastal management framework.

A third gap is the lack of a consistently applied national framework for comparing blue carbon stocks across ecosystems and locations. Published studies use different sampling designs, carbon pools, sediment depths, analytical approaches, and reporting units. These methodological differences make direct comparison difficult and limit the development of a reliable national-scale assessment. The need for standardized carbon accounting, monitoring, and verification is therefore a major research priority.

A fourth gap relates to monitoring and restoration assessment. Remote sensing and GIS have considerable potential for mapping coastal ecosystems and detecting changes over time, but their integration with field-based carbon measurements and long-term ecological monitoring remains limited in Bangladesh. A stronger combination of satellite observations, field measurements, carbon-stock assessments, and community-level information could provide a more comprehensive basis for conservation planning.

A fifth gap concerns the social and institutional dimensions of blue carbon conservation. Coastal communities depend heavily on mangrove and wetland ecosystem services while simultaneously experiencing high exposure to cyclones, salinity intrusion, erosion, and other environmental pressures. However, ecological carbon assessments are not always

sufficiently connected with community participation, livelihood considerations, governance, and benefit-sharing mechanisms. Integrating these dimensions is important for ensuring that conservation and restoration strategies are socially appropriate and sustainable.

Novelty and Added Value of This Review

The novelty of this review does not lie in producing a new field measurement of carbon stocks. Instead, its contribution is to provide an integrated synthesis of existing evidence specifically from the perspective of blue carbon conservation and coastal management in Bangladesh.

First, the review brings together evidence on mangroves, salt marshes, and seagrass ecosystems within a common blue carbon framework, while explicitly identifying differences in the availability and quality of evidence among these ecosystems. This approach helps demonstrate where Bangladesh has relatively strong scientific knowledge and where important evidence gaps remain.

Second, the review connects blue carbon sequestration with coastal resilience and ecosystem services rather than treating carbon storage as an isolated climate-mitigation outcome. Carbon storage, shoreline stabilization, biodiversity conservation, fisheries support, and community resilience are considered as interconnected components of coastal ecosystem management.

Third, the review critically examines the relationship between ecosystem conservation, restoration, carbon accounting, remote sensing, community participation, and policy implementation. This provides a management-oriented perspective that can help connect ecological research with practical coastal conservation planning.

Fourth, the review identifies the methodological limitations that currently restrict comparison among Bangladesh's blue carbon studies, including differences in carbon pools, sampling approaches, spatial coverage, and monitoring periods. Rather than combining heterogeneous estimates into a single national value, the review highlights the need for standardized assessment protocols and long-term monitoring.

Finally, the review develops a research and management agenda for Bangladesh centered on five interconnected priorities: (i) establishing a national blue carbon inventory, (ii) expanding research beyond the Sundarbans to salt marshes and seagrasses, (iii) integrating remote sensing and field-based carbon monitoring, (iv) strengthening community-based and ecosystem-based restoration, and (v) improving the integration of blue carbon into coastal conservation and climate policy.

Thus, the added value of this review is its integrated Bangladesh-specific perspective, linking the scientific evidence on blue carbon storage with conservation, coastal resilience, restoration, monitoring, community participation, and policy needs. Rather than presenting blue carbon solely as a carbon-sequestration opportunity, the review evaluates it as a component of broader coastal ecosystem conservation and management.

10: Conclusion

Blue carbon ecosystems represent an important component of Bangladesh's nature-based approach to climate mitigation and coastal conservation. The country's extensive mangrove and other coastal ecosystems store substantial amounts of carbon in vegetation, roots, and, particularly, coastal sediments while simultaneously providing ecosystem services that support coastal protection, biodiversity, fisheries, and local livelihoods. The Sundarbans is especially significant because of its ecological importance and its capacity to retain carbon within biomass and sediment.

The evidence reviewed in this study indicates that conserving existing mangrove ecosystems should remain a central priority because protection avoids the loss and potential release of previously stored carbon while maintaining multiple coastal ecosystem services. Restoration of degraded mangrove areas can complement conservation, particularly where hydrological conditions, sediment supply, salinity, land tenure, and community participation are appropriately considered. However, restoration should not be viewed simply as tree planting; successful blue-carbon management requires ecosystem-based planning that maintains natural tidal processes, suitable species composition, and long-term ecological functioning.

For Bangladesh, the climate-mitigation value of blue carbon should be considered alongside its broader coastal-conservation functions. Integrating blue-carbon considerations into coastal planning, ecosystem restoration, climate adaptation, and national climate-policy frameworks could strengthen the connection between ecosystem conservation and climate action. Improved coordination among government institutions, researchers, local communities, and conservation organizations is also important for implementing durable management strategies.

Nevertheless, current evidence is constrained by differences in carbon-accounting methods, limited long-term field observations, spatial gaps in national datasets, and uncertainty surrounding carbon permanence and greenhouse-gas fluxes. These limitations prevent precise estimation of the national mitigation potential of Bangladesh's blue-carbon ecosystems. Future research should therefore prioritize a standardized national blue-carbon inventory, harmonized field protocols, remote-sensing and GIS-based monitoring, long-

term carbon and greenhouse-gas measurements, and assessment of less-studied coastal ecosystems such as seagrass and tidal wetlands.

Overall, blue carbon should be approached as a complementary nature-based strategy rather than a standalone solution to Bangladesh's climate challenges. Its greatest contribution may come from linking carbon conservation with coastal resilience, biodiversity protection, sustainable livelihoods, and ecosystem-based management. A scientifically robust and locally appropriate blue-carbon framework could help Bangladesh strengthen coastal conservation while supporting its broader climate-mitigation and adaptation objectives.

Chapter 10: References

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