HSPI The Open Access Publisher

ACEE ISSN 2574-0350 ANNALS OF CIVIL AND ENVIRONMENTAL ENGINEERING

Research Article

Ocean Carbon Sequestration and Blue Carbon Ecosystems for Climate Mitigation: Scientific Evidence, Policy Integration and Opportunities for India

Panna Chandra Nath*

Mobius Foundation, New Delhi, India

Abstract

World oceans play an important role in regulating the planet's climate through sequestering atmospheric CO_2, heat absorption, and the maintenance of biogeochemical cycles. In recent decades, blue carbon ecosystems such as mangroves, seagrasses, salt marshes, and marine primary producers have received increased attention due to their capacity to sequester carbon while simultaneously supporting biodiversity, coastal protection, and local livelihoods. The entire system sequesters almost one-third of CO_2 emissions from human activity and most of the excess heat trapped in the atmosphere. This review evaluates current scientific evidence on oceanic carbon sequestration and the contribution of blue carbon ecosystems to climate mitigation and adaptation. It further examines the integration of ocean-based climate solutions into climate governance frameworks highlighting opportunities, challenges, and policy significance for mainstreaming blue carbon within India's climate strategies. While recognition of blue carbon has increased considerably within scientific and policy communities, significant implementation gaps remain, particularly in monitoring, reporting, verification, financing, and long-term ecosystem protection. The review also discusses major uncertainties associated with blue carbon accounting and permanence. The paper proposes a framework for strengthening the integration of ocean-based climate solutions into national and international climate strategies and identifies key priorities for research, policy development, and ecosystem restoration.

More Information

***Corresponding author:** Panna Chandra Nath, Mobius Foundation, New Delhi, India, Email: pcnath722@gmail.com

https://orcid.org/0000-0002-9983-9564

Submitted: November 11, 2026
Accepted: November 14, 2026
Published: November 16, 2026

Citation: Nath PC. Ocean Carbon Sequestration and Blue Carbon Ecosystems for Climate Mitigation: Scientific Evidence, Policy Integration and Opportunities for India. Ann Civil Environ Eng. 2026; 10(1): 37-45. Available from: https://dx.doi.org/10.29328/journal.acee.1001092

Copyright license: © 2026 Nath PC. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Keywords: Blue carbon; Ocean carbon sequestration; Climate mitigation; Coastal ecosystems; Nature-based solutions

Check for updates

OPEN ACCESS

Introduction

Anthropogenic climate change is primarily driven by increasing concentrations of greenhouse gases, particularly carbon dioxide (CO_2). Most of the mitigation efforts were traditionally focussed on the reduction of emissions from the energy systems, transportation, industry and land use change. Increasing attentions has also been directed towards conservation of natural carbon sinks additionally have the potential to complement the existing emission reduction strategies. The Earth's oceans act as the planet's largest carbon sponge, absorbing about 25–30% of annual CO_2 emissions produced by human activities [1], and more than 90% of the excess heat that is trapped by greenhouse gases [2] to keep the temperature cooler. Through a combination of physical, chemical and biological processes from the surface to the depths [1], ocean regulates atmospheric carbon concentrations, and influences global climate stability. Simultaneously, marine ecosystems such as, mangroves, seagrasses, and salt marshes, have also gained significant scientific attention because of their ability to store carbon over long timescales in both biomass and sediments. By moderating temperature and shielding against climate extremes, the oceans act as the major regulators of the global climate system.

Recent studies show that long term warming of the ocean is closely associated with the scale at which oceans are up taking excessive heat and the vulnerability of the marine ecosystems due to climate stress [2]. With the increase in climate crisis, role of the oceans becomes more significant when mitigation and adaptation is becoming increasingly urgent.

The important factors of the ocean-based climate regulations are diverse and dynamic ecosystems like mangroves, seagrasses, salt marshes, etc., collectively called as blue carbon ecosystems, and they can store carbon at rates up to 10 times higher than terrestrial forests and can store it more permanently by sequestering carbon in seabed sediments

[3-5]. In addition, the blue carbon ecosystems provide significant co-benefits, which include protection to the coastal areas, biodiversity conservation, and livelihood support to the local communities [6]. Further, the phytoplankton communities of the blue carbon ecosystems have significant carbon sequestration potential and sequester gigatons of carbon despite being a small fraction of the global biomass. The oceans have an estimated stock of 38,000 Pg of carbon, which makes it the world's largest carbon storehouse and is significantly larger than the other ecosystems [7]. Despite their critical role in sequestering atmospheric CO_2, significant challenges still exist regarding the incorporation of blue carbon into climate mitigation frameworks. Inadequate monitoring approaches, uncertainties in carbon accounting limited their integration into the Nationally Determined Contributions (NDCs), also the insufficient funding mechanisms further strains the large-scale implementations [8].

Anthropogenic pressure, like coastal development, pollution, overexploitation, and warming of the oceans are degrading the marine carbon sink and additionally increasing threats to their long-term carbon sequestration potential [1,6]. In coastal countries like India, this emerged as both vulnerability and opportunity. With extensive coastline and climate-sensitive coastal communities, the mangrove ecosystems of India showed significant carbon sequestration potential alongside supporting biodiversity conservation and livelihood security [9]. Integrating ocean-based climate solutions into the climate regulation strategies help attaining the mitigation and adaptation outcomes of the policies. This review, therefore, critically evaluates current scientific evidence on oceanic carbon sequestration and the contribution of blue carbon ecosystems to climate mitigation and adaptation. It also examines the integration of ocean based climate solutions into international climate policy frameworks, highlights the important scientific and policy uncertainties associated with blue carbon ecosystems, and explore opportunities for strengthening their implementation. Recognizing India's extensive coastal blue carbon ecosystems and growing emphasis on nature-based climate solutions, the review also examines the opportunities and challenges for incorporation of blue carbon into India's climate policy and coastal management strategies. Collectively highlighting global perspectives with focusing in India, this review aims to provide evidence-based recommendations for strengthening ocean-based climate action at both national and international levels.

Based on the available scientific evidence and policy developments, this review is guided by the hypothesis that integrating ocean carbon sequestration and blue carbon ecosystems into climate mitigation and adaptation strategies can strengthen climate action. However, this requires reliable carbon accounting, proper monitoring, reporting, and verification (MRV) systems, supportive policies, adequate financial support, and active involvement of coastal communities. The review also considers that India has considerable potential to promote this approach by protecting and restoring its coastal ecosystems and including them in national climate and coastal management strategies.

Review scope and methodology

This review article analyses peer-reviewed scientific literatures, international assessment reports, policy documents, and government reports on or related to ocean carbon sequestration and blue carbon ecosystems. Different platforms like, Web of Science, Scopus, Google Scholar, and ScienceDirect were explored for the relevant scientific literatures using different and combinations of keywords which include blue carbon, ocean carbon sequestration, marine carbon sink, mangroves, seagrasses, salt marshes, macroalgae, phytoplankton, climate mitigation, ocean-based climate solutions, Nationally Determined Contributions, India, and blue economy. Articles and reports were selected based on their relevance with carbon storage, carbon sequestration, climate mitigation potentials, ecosystem services, policy integration, and challenges to implementation, and published after 2000. Additionally, important reports of IPCC, UNFCCC, UNEP, FAO, NOAA, Government of India, and bibliographies of relevant review articles and policy documents on the subject were accessed to identify current policy frameworks and developments regarding blue carbon ecosystems.

Ocean carbon sequestration

The global carbon cycle is relatively incomplete without oceans because they potentially sequester atmospheric CO_2 through physical absorption, where CO_2 is directly dissolved into the ocean's salt water, and biological absorption, where planktons, algae, seagrass, etc., sequester CO_2 through photosynthesis. Carbon sequestered through biological absorption gets almost permanently stored deep in the ocean in the seabed through decomposition upon their death. Seagrasses, mangroves, and salt marshes, collectively known as the blue carbon ecosystems, can store carbon both in biomass and sediments.

Research estimates that seagrass meadows have a significant carbon stock of 199×10^8 Mg (19.9 Pg) despite occupying nearly 0.1% of the ocean floor [3]. Similarly, the mangrove forests have a total carbon stock of around 956 Mg C ha^{-1}, which is significantly more than the carbon sequestered in the tropical forests (~241 Mg C ha^{-1}) [4]. A comprehensive study from Kerala showed that these mangroves can maintain an average biomass stock of 117 Mg ha^{-1}, which accounts for 139.8 Mg C ha^{-1}, or around 513 Mg CO_2 eq ha^{-1}, combining both vegetation and soil carbon [9]. Global mangrove habitats cover around 135,000 to 150,000 km^2 in more than 118 countries in Southeast Asia, South America, Africa, and the Caribbean. These systems cumulatively have stock of organic carbon ranging approximately from 5.2–8.6 Pg , and they bury 9.6–15.8 Tg C per year, about 4–5 times more carbon than comparable upland forests [6].

Phytoplanktons also play a critical role in global carbon cycle. Although they occupy a small proportion of global biomass, yet they contribute nearly half of the global primary production, and are a major pathway for atmospheric carbon sequestration [10]. Phytoplankton Climate-smart agriculture, ecosystem restoration, climate adaptation, environmental impact assessment, potentially sequesters around 45 Pg of carbon annually, accounting for 20% of the planet's total CO_2 [11,12], though they represent roughly 1% of the Earth's plant biomass [13]. Upon their death, the carbon contained in them gets permanently stored in the ocean sediment bed or through marine food chains. On the other hand, the macroalgae, commonly known as seaweed, grow rapidly and their growth may reach up to 50 cm day^{-1}. Studies suggest that they encompass nearly 9% of the ocean and could potentially sequester around 53 Gg of CO_2 annually [14].

In addition to global significance, India possess around 4992 km^2 of mangrove forest, 517 km^2 of seagrass, while salt marshes range from 290–1398 km^2 having significant uncertainty in spatial distribution patterns of salt marshes and seagrasses [15-17]. A meta-analysis has recently estimated that these blue carbon ecosystems collectively sequestered approximately 67.35 Tg C, of which mangroves account for about 67 Tg C, which highlights their significance on the country's blue carbon reserve. Yet, nearly 50% of these remained less assessed for carbon stock estimation [18]. In total, the world's oceans have an estimated stock of around 38,000 Pg (Gt) of carbon, which is approximately 16 times more than all the terrestrial carbon stocks, including that in plants and soil combined. Furthermore, it is 60-fold higher than the atmospheric carbon concentration before the beginning of the Industrial Revolution [7].

Comparative assessment of blue carbon ecosystems

The blue carbon ecosystems significantly differ in accordance with their geographic location and distribution, carbon sequestration, and associated ecosystem services. Among them, mangrove forests are the most extensive studied blue carbon ecosystem, because of their extensive root systems, high productivity, and their potential to trap sediment enables considerable carbon storage on both biomass and soils [19]. In addition, seagrass meadows represent another globally significant carbon sink despite their less area of extent (160387 km^2) while comparing with the forests (46.62 million km^2) [20,21]. On the other hand, salt marshes have high carbon accumulation rates (approximately 2.4 Mg ha^{-1} yr^{-1}) in to the sediments and are recognised for their significant contribution in coastal resilience [22]. Algae, Seaweed, and phytoplankton have significant contribution in carbon sequestration through rapid growth and are important part of the ocean carbon linkages (Table 1).

Though mangrove, salt marshes, seagrass have important contributions to carbon sequestrations, but, information to their carbon stocks varies across India. Among all the blue carbon ecosystems, mangroves have received significant attentions (yet limited) due to their wide distributions and having established national inventories. Consequently, uncertainties in ecosystem extent and carbon storage are considerably higher for seagrasses and salt marshes, which emphasises the need for comprehensive field surveys and standardized assessment protocols prior to incorporation of these ecosystems into India's national greenhouse-gas accounting and blue carbon policies [18,23].

Policy integration of blue carbon in climate agreements

Ocean based climate mitigation has received sincere attention since the last decade, yet, global climate agreements majorly highlights forests, emission targets, and technology innovations [24]. The international initiatives like, the United Nations Convention on the Law of the Sea (UNCLOS), the International Convention for the Prevention of Pollution from Ships (MARPOL), and the United Nations Ocean Conference (UNOC) have started growing emphasis for countries to protect the marine environment using nature-based solutions [25]. Which includes, mangrove restoration, seagrass meadow conservation, salt-marsh rehabilitation, living shorelines, and integrated coastal wetland management. These approaches can simultaneously increase the ecosystems carbon sequestration, reduction in coastal erosion, improve biodiversity, and strengthen resilience to climate change. Yet, without a clear link to the UNFCCC or the Paris Agreement, and global climate efforts, impact on wider climate goals remains limited and disconnected from broader environmental action [26,27]. Nevertheless, significant differences remain in the extent to which countries incorporate blue carbon ecosystems into national climate strategies. While many Nationally Determined Contributions (NDCs) recognize the importance of coastal ecosystems, relatively few provide explicit quantitative targets for carbon sequestration, restoration, or monitoring. For example, India's NDCs include reducing emissions intensity by 45% below 2005 levels by 2030 and achieving 50% of its electricity capacity from non-fossil fuel sources by the same year, with exclusively no mention of mangroves restoration or seagrass restoration or reducing ocean acidification to target increasing the carbon capture by phytoplankton and other algae [28]. Approximately, 41 parties (21% of all Parties to the Paris Agreement) currently include blue carbon or coastal ecosystems within their NDCs. Because many Parties are landlocked or possess limited coastal blue carbon ecosystems [29]. Among which, the Seychelles gave advanced and specific targets of protecting 50% of the Blue Carbon habitats and increasing it to 100% by 2030 [30]. Belize, Mexico [31] and Costa Rica [32] have also recognised coastal in their NDCs, however a quantitative carbon accounting framework is limited [33] (Table 2). While the United Nations Ocean Conference is very new, it aims to protect 30% of the ocean jointly with the land by 2030, and reverse the losses to nature by the same year [34]. However, its implementation largely depends on the surplus of the

Table 1: Comparative characteristics of major blue carbon ecosystems.

Ecosystem	Carbon Stock/ Sequestration Potential	Carbon Storage Mechanism	Major Co-benefits	Key Uncertainties
Mangroves	Carbon stock: ~956 Mg C ha^{-1}; Sequestration rate: 9.6–15.8 Tg C yr^{-1}	Biomass and sediments	Coastal protection, fisheries support, biodiversity conservation, livelihood security	Land-use conversion, coastal development, permanence of stored carbon
Seagrasses	Carbon stock: 19.9 Pg; Sequestration rate: 33 g C m^{-2} yr^{-1}	Primarily sediments	Water quality improvement, habitat provision, shoreline stabilization	Mapping uncertainties, habitat degradation
Salt Marshes	Carbon Sequestration rate: ~2.4 Mg ha^{-1} yr^{-1}	Sediments	Flood mitigation, coastal resilience, habitat support	Vulnerability to sea-level rise and land-use change
Macroalgae (Seaweeds)	Carbon Sequestration rate: ~53 Gg CO_2 yr^{-1}	Biomass production and export to deep ocean	Habitat creation, nutrient cycling, fisheries support	Uncertainty regarding long-term carbon fate and permanence
Phytoplankton	Carbon Sequestration rate: ~45 Pg C yr^{-1}	Biological carbon pump	Supports marine food webs and global carbon cycling	Uncertainty in carbon export efficiency and long-term sequestration

Source: Compiled from [3,4,6,12-14,20,22]

Table 2: Examples of blue carbon integration in Nationally Determined Contributions (NDCs).

Country	Blue Carbon Included	Quantitative Target	Monitoring Framework
Seychelles	Yes	Yes	Partial
Costa Rica	Yes	Limited	Partial
Belize	Yes	Limited	Partial
Mexico	Yes	Limited	Partial
India	Limited	No explicit target	Developing

The countries were selected to illustrate difference in integration of blue carbon policy within NDC's. Countries having well-developed blue carbon policies (e.g., Seychelles, Belize), significant progress in integration of blue carbon policies (Costa Rica, Mexico), and countries having significant blue carbon resources but limited explicit policy recognition (India).

allocation of funds and the conservation rigour of the parties. Because after decades of conservation efforts through CBD, it is documented that only 8.2% of the world's ocean and coastal areas are under designated protected areas [35]. The growing recognition of blue carbon within climate governance showed significant progress compared to previous decades, however, achieving a significant climate impact will require integration between scientific evidence, ecosystem restoration programs, carbon accounting systems, and climate policy frameworks.

The importance of coastal ecosystem has been increasingly recognised by India through different initiatives such as the Mangrove Initiative for Shoreline Habitats and Tangible Incomes (MISHTI), the National Coastal Mission, and mangrove restoration programmes implemented by several coastal states. Nevertheless, blue carbon has not yet been explicitly incorporated into India's Nationally Determined Contribution (NDC) [17,18]. This indicates opportunities for India to integrate accounting of ecosystem carbon, monitoring, reporting and verification (MRV), and restoration targets into future climate commitments.

Risks and challenges associated with loss of the blue carbon ecosystems

The impact of degradation extends beyond biodiversity conservation and directly affects climate regulation, coastal resilience, and socioeconomic well-being. Due to the continued stress on the blue carbon ecosystems through land-use change, pollution, unsustainable fishing practices in addition to climate related stress, their capacity to sequester and store carbon may decline significantly. Among the consequences, ocean acidification is most widely documented. Since the beginning of the industrial revolution, ocean absorption of anthropogenic CO_2 has altered the water chemistry of the oceans. This resulted in a noticeable reduction in the pH level from 8.11 to less than 8.05 between 1950 and 2020, indicating a sharp 26% increase in hydrogen ion concentrations. This change is due to nearly 25% of anthropogenically emitted CO_2 being absorbed by the ocean water, as ocean acidification has increased by more than 40% since the pre-industrial level [36]. Consequently, the ocean acidification, together with warming and the reducing levels of dissolved oxygen, significantly disrupts the marine food chain, thereby impacting phytoplankton's productivity [37] and their ability to sequester CO_2 [38]. If the consequences remain unchecked, it will lead to interacting stressors of warming, acidification, and deoxygenation threatening the marine ecosystem, which in turn impacts their resilience against a changing climate.

In addition, fishing activities, more specifically overfishing, have released a significant amount of stored carbon from the world's oceans to the atmosphere. Also, the fishing vessels release lakhs of tonnes of CO_2 to the atmosphere than the entire EU emits annually (7.3 million tonnes) from burning fossil fuels [39]. The situation further deteriorates with the destructive fishing like bottom trawling, which alone accounts for 370 million metric tonnes of CO_2 being released back to the atmosphere from the ocean beds [40].

On the other hand, in addition to the extensive carbon sequestration potential of the mangrove ecosystem, they also provide a frontline protective shield to the coastal regions from storms. A 100 m of mangrove forest holds enough potential to reduce the ocean's wave energy up to 66% protecting coastal damages annually, which may be worth up to USD 65 billion, and can protect 15 million people across the globe [41]. Oceans are well recognised for their ability to regulate temperature. They absorbed up to 90% of the excess heat attributed to burning fossils since the 1970s [42], thereby making a buffer from the extreme warmings [43]. These massive potentials

of the oceans have largely been ignored globally, and lead to massive, serious, and cascading consequences. The reduced capacity of absorbing excessive heat due to acidification, warming, and deoxygenation can intensify marine heatwaves, reduce fisheries productivity, and disrupt monsoon patterns, which are crucial for agricultural economies like India. Additionally, degradation of the massive carbon stock reducing its carbon sequestration potential increases the risks for setting a significant chain of emissions >1 Gt of CO_2 from disturbed seabed annually, which is equivalent to the cumulative emissions from the entire aviation sector [44]. For countries such as India, where millions of people depend directly or indirectly on coastal resources, degradation of blue carbon ecosystems may have significant implications for food security, livelihoods, disaster risk reduction, and long-term climate resilience.

Ocean-based climate solutions

In harnessing the ocean's climate potential, the path forward should integrate science, policy, and community action. Recently, nature-based solutions such as mangrove, seagrass, and salt marsh restoration practices have gained significant attention. According to the World Wildlife Fund (WWF), the mangroves in an acre can store up to 7.5–10 folds more carbon than the tropical forests [45], and Seagrass's carbon sequestration potential could reach up to 1.33 Mt C ha^{-1} yr^{-1} with 33 g C m^{-2} yr^{-1}, which is equivalent to the estimated CO_2 emissions from running a combustible automobile for around 2500 km [46]. While the actual global impact of industrial fishing across the globe has not been investigated adequately, yet the CO_2 emission from the practice in the European waters alone ranges from €330 million to €11 billion per year (€1 = $1.17) [47]. To curb these factors, a proposal of $100 billion was forwarded in the UNOC 3 (Third United Nations' Ocean Conference), especially to minimise the bottom trawling and associated release of CO_2 from the practice [48]. In a similar effort, the Ministry of Environment, Forests, and Climate Change, Government of India, during the years 2017–2018 and 2022–2023, sanctioned a total grant of ₹220.43 lakhs to the Government of Tamil Nadu for the restoration of the mangrove ecosystem across its coastline [49]. This programme includes formal MRV frameworks involving local fishing communities.

The Indian subcontinent provides several scalable ocean-based climate solutions. To enhance coastal resilience and ecosystem services large scale mangrove restoration programmes have been implemented in the states of Gujarat, Odisha, West Bengal, Tamil Nadu, and Andhra Pradesh [17]. The Government of India's Mangrove Initiative for Shoreline Habitats & Tangible Incomes (MISHTI) initiative aims to eco-restore around 540 km^2 of coastal habitats through the central and the state's Compensatory Afforestation Fund Management and Planning Authority (CAMPA) funds. A recent ecological assessment from the Adyar Estuary (Tamil Nadu) showed that the 56.6 acres of the restored mangrove forest have achieved a high tree density of 3900 tree ha^{-1}, and the growing ecosystem have significantly sequestered 2,288 tonnes of carbon [50]. These developments highlights the increasing potential of the country to implement the restoration to practical conservation and restoration programmes.

Recent studies highlight the importance of blue carbon ecosystems and the need to improve their scientific assessment and policy integration. They also highlighted the importance of mangroves, seagrasses and salt marshes as carbon sinks, while also pointing to gaps in the availability of reliable information on their extent and carbon stocks [16,18]. Emphasises are on the value of improving ecosystem-level assessment and adopting consistent approaches to carbon measurement and monitoring [19,23]. These findings are consistent with the present review, which identifies differences in carbon estimates and limited monitoring information as important barriers to including blue carbon in national climate strategies. The review also finds that recognition of coastal ecosystems does not always translate into clear carbon targets, regular monitoring or measurable implementation plans. It also suggests the need to connect scientific evidence with national climate commitments, restoration programmes and long-term financial support. In India, initiatives such as MISHTI provide an opportunity to strengthen mangrove restoration, however, significant progress will also require better assessment of seagrass and salt-marsh ecosystems, reliable carbon accounting, effective monitoring, reporting and verification (MRV), and the meaningful participation of coastal communities. Overall, the study suggests that the challenges identified in this review are consistent with those reported in recent research, while also highlighting the need for a more coordinated approach to blue carbon conservation and climate policy in India.

Limitations and uncertainties in the blue carbon assessment

Blue carbon ecosystems have come up as encouraging nature-based climate solutions, yet there exist some considerable uncertainties on their quantification, stability, and implementations in the policies. Therefore, these uncertainties should carefully be considered while incorporating blue carbon in climate frameworks. A major limitation was observed regarding the carbon stock estimation. Due to difference in the sampling strategy, depth of the system, ecosystem characteristics, and regional environmental variations, the reported values of carbon stock differ between studies [51]. For example, a significant proportion of the ecosystem carbon stock remained unaccounted as most of the assessments solely rely on the above ground biomass, which generally underestimates the overall ecosystem carbon where, a significant stock extends beyond 1 m depth of the sediments [52]. Similarly, with the difference in sediment coring depths, the laboratory techniques like loss-on iginition, elemental

analysis, sampling intensity, and site selection contribute to considerable variability among published carbon stock estimates. In addition, blue carbon ecosystems are mostly vulnerable to disturbances such as, cyclones, coastal erosion, sea-level rise, aquaculture expansion, urbanization, and infrastructure development [53]. Which further increases the volume of uncertainty on the stability of the carbon stock.

MRV is another additional challenge in the blue carbon assessment. Blue carbon ecosystems lack a standard, polished, mature protocol for carbon sequestration estimation [54], which further increases the limitation constraints to integrate blue carbon into national greenhouse gas inventories and carbon markets. Moreover, carbon finance mechanism relies on increased sequestration of atmospheric CO_2 through restoration and conservation efforts rather than the normalised sequestration under the current systemic stability for any ecosystem [55]. Establishment of such additional increments remains an additional challenge for the dynamic blue carbon ecosystems. Therefore, to address these uncertainties the monitoring technologies required to be improved with standardised assessment methodologies, long term ecological studies, and stronger ecological cooperation and shared vision for blue carbon assessment and reporting .

In addition, uncertainties regarding assessment protocols of blue carbon ecosystems are also relevant in India as the carbon stock assessments are spatially uneven across the country. Recent studies reported that almost 50% of the mangrove forests in the country have been examined for ecosystem carbon stock, whereas reports on seagrass and salt marshes are fragmented. Further, inconsistencies in sediment sampling depth, biomass estimation methods, and laboratory estimation methods have contributed significant variation among the stock results published. This highlights the need of standardised protocol for blue carbon assessment and long-term monitoring at the national level [18,23].

In addition to the uncertainties discussed above, this review has some limitations that should also be considered when interpreting its findings. As the study is based on published literature and policy documents, the findings depend on the availability, quality, and coverage of the existing sources. The selection of studies may also have introduced some bias, as research from certain regions and ecosystems is more widely available than research from less-studied coastal areas. In the Indian context, the limited and uneven availability of carbon stock data, particularly for seagrass meadows and salt marshes, may affect the completeness of the national-level assessment [18]. Differences in study objectives, sampling methods, sediment depth, and carbon estimation techniques also make direct comparisons between published results difficult [51]. Furthermore, this review does not independently verify the reported carbon estimates or assess the implementation and long-term outcomes of individual restoration projects. Therefore, the findings should be understood as an evidence-based synthesis of the available information rather than a comprehensive or standardised measurement of blue carbon resources. Future research should focus on more balanced regional assessments, consistent carbon measurement methods, long-term monitoring, and transparent reporting of restoration outcomes.

India as a case study: opportunities and challenges

Having an extensive coastline stretching approximately 7,516 km across 13 states and union territories, India have some important case study to examine the challenges and opportunities associated with the integration of blue carbon into the climate policies. Surrounded with diverse coastal ecosystems distributed across Arabian Sea, Bay of Bengal, and island territories, India have significant blue carbon resources that can contribute to both climate mitigation and adaptation objectives. The country has around 4,992 km^2 of mangrove forest concentrated primarily in the Sundarbans, Gujarat, Andhra Pradesh, Odisha, Maharashtra, and the Andaman and Nicobar Islands, which stores about 339.51 lakh tonnes of carbon in just 0.15% of land cover [57]. Blue carbon sequestration potential of India stands around 702 Mt CO_2 eq, and efforts are being made to raise the storage potential by 208 Mt CO_2 eq by the year 2030, which will be roughly comparable to 22% of the present annual emissions of the country [58]. In addition to carbon sequestration potentials, these ecosystems also support fisheries, biodiversity conservation, coastal stabilisation, and protection against storms. However, the mangrove ecosystems are considerably fragile, Kerala have lost around 98% of its mangrove cover in the last 50 years, and Sundarbans lost around 110 km^2 in just 20 years [59,60].

In terms of policy perspectives, India showed increasing engagement with blue carbon initiatives by joined the Mangrove Alliance for Climate (MAC) at the 27th Conference of the Parties (COP27) of the UNFCCC held in Sharm el-Sheikh, Egypt. The state-level initiatives, especially in Tamil Nadu, have further presented the potential for ecosystem restoration with community participation and climate adaptation strategies [50]. Where, government supported mangrove restoration programs have incorporated ecosystem monitoring, community engagement, and scientific assessment. These growths provide important and valuable insights into the design and implementation of blue carbon restoration programmes in other coastal states in the country. Having these developments in the blue carbon restoration and management efforts, blue carbon partially integrated in the country's climate policies [61]. Similarly, comprehensive MRV for marine carbon sequestration are still under development [62]. Regionally, the blue carbon ecosystem can act as a buffer against coastal flooding, support local fisheries, and enhance livelihood security, while also strengthening India's climate commitments and improving its global standing as a climate leader.

India have diverse opportunities to strengthen its ocean-

based climate policies and actions such as, developing national blue carbon inventories, integration of coastal ecosystems into greenhouse gas accounting framework, expansion of restoration initiatives, improvement MRV infrastructure, mobilising climate finance through different bonds (eg. Blue Bonds), and voluntary carbon markets. Adopting these strategies could strengthen India's climate commitments and regional coastal resilience.

Proposed framework for mainstreaming blue carbon into climate polices

While existing blue carbon policy frameworks that primarily focuses on conservation of the ecosystems or assessment of the carbon stocks only, the framework proposed in this review incorporates scientific assessment, MRV systems, policy mainstreaming, climate finance, restoration actions, and governance within a unified implementation pathway. Further, this study also connects these components to the Indian policy landscapes thereby guiding integration of blue carbon ecosystems into national climate mitigation and adaptation strategies extending its applicability to other coastal countries.

Based on the synthesised findings, to include blue carbon ecosystems into climate mitigation strategies, a framework should have the following components:

- **Ecosystem assessment**: To understand the baseline carbon stocks and to identify the restoration priorities, precise mapping of blue carbon ecosystems such as mangroves, seagrass, salt marshes, etc. is required.
- **Carbon accounting**: Polished and standardised methodologies are equally essential to quantify carbon sequestration, reduction in carbon efflux, and to maintain consistency regions regarding carbon reporting systems.
- **MRV**: To increase transparency, enhance credibility of the policy, and to facilitate integration into national greenhouse gas inventories and carbon finance mechanisms, a robust MRV system is required.
- **Policy integration**: Blue carbon components should be integrated at the governance level, especially in the NDCs, coastal zone management plans, biodiversity strategies, and adaptation frameworks at national level.
- **Finance and implementation**: Adequate long-term conservation and restoration require sustainable funding, which includes public investment, climate finance mechanisms, blue bonds, debt-for-nature swaps, and voluntary carbon markets.

Conclusion

This review aimed to examine the scientific evidence on ocean carbon sequestration and blue carbon ecosystems, assess their integration into climate policies, and identify opportunities and challenges, with particular reference to India. The review was guided by the hypothesis that integrating ocean carbon sequestration and blue carbon ecosystems into climate mitigation and adaptation strategies can strengthen climate action, provided that reliable carbon accounting, effective MRV systems, supportive policies, adequate financial support, and community participation are in place. The findings broadly support this hypothesis. The review highlights the important role of ocean and coastal ecosystems in climate regulation and shows that their effective contribution to climate action depends on stronger policy integration, improved carbon assessment and monitoring, sustainable financing, and long-term conservation. In the Indian context, the findings also indicate considerable potential to advance this approach, although further improvements in carbon accounting, MRV systems, and policy implementation are needed.

Oceans plays a fundamental and critical role to regulate earth's climate through carbon sequestration by absorbing one-third of total anthropogenic carbon emissions and more than 90% of the excess heat. In this process, ecosystems like mangroves, seagrasses, salt marshes, and other primary producers like planktons and algae contribute important roles together with sustaining biodiversity, livelihood, and coastal protection benefits.

The review highlighted the increased recognition of the blue carbon significantly since the last decade, yet significant challenges exists on policy integration, carbon accounting, MRV, finances, and long-term conservation strategies. Several countries have incorporated blue carbon and coastal ecosystem management into their climate adaption and management strategies, however, implementation of the strategies is uneven, and therefore, blue carbon targets are limited in many NDCs.

India, on the other hand, highlights both opportunities and challenges while incorporating blue carbon into its climate strategies and policies. However, having extensive coastline, significant mangrove resources, increasing restoration initiatives provide a string foundation future adaptation and mitigation strategies. There is a wide scope to significantly strengthen India's mitigation and adaptation outcomes by ecosystem assessment, improving MRV systems, expanding restoration efforts, and integrating blue carbon into climate policies.

Blue carbon ecosystems are likely to play an increasingly important role within integrated climate mitigation and adaptation strategies at both national and global scales. However, full potential of these frameworks will require transboundary collaboration among scientists, policymakers, coastal communities, international organizations, and financial institutions.

Competing interests: The authors declare no competing interests.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement: Data sharing is not applicable to this article as no new data were created or analysed in this study.

References

1. Hoegh-Guldberg O, Cai R, Poloczanska ES, Brewer PG, Sundby S, Hilmi N, et al. The ocean. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, et al., editors. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Cambridge (UK): Cambridge University Press; 2014. p. 1655-1731. Available from: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap30_FINAL.pdf
2. Mooney A, Bernard S. World's oceans remain near record temperatures as CO_2 levels rise. Financial Times. 2025 Jul 13. Available from: https://www.ft.com/content/cfe4757a-a054-49ce-b850-a154e543b7ba
3. Fourqurean JW, Duarte CM, Kennedy H, Marba N, Holmer M, Mateo MA, et al. Seagrass ecosystems as a globally significant carbon stock. Nat Geosci. 2012;5:505-509. Available from: https://doi.org/10.1038/ngeo1477
4. Alongi DM. Carbon cycling and storage in mangrove forests. Annu Rev Mar Sci. 2014;6:195-219. Available from: https://doi.org/10.1146/annurev-marine-010213-135020
5. NOAA. Coastal Blue Carbon [Internet]. National Ocean Service; 2024 [cited 2025 Jul 13]. Available from: https://oceanservice.noaa.gov/ecosystems/coastal-blue-carbon/
6. Hilmi N, Carranco MBB, Broussard D, Mathew M, Djoundourian S, Cassotta S, et al. Tropical blue carbon: solutions and perspectives for valuations of carbon sequestration. Front Clim. 2023;5:1169663. Available from: https://doi.org/10.3389/fclim.2023.1169663
7. World Ocean Review. Living with the oceans: a report on the state of the world's oceans [Internet]. 2010 [cited 2025 Jul 13]. Available from: https://worldoceanreview.com/en/wor-1/ocean-chemistry/co2-reservoir/#:~:text=TheoceanCwitharound38%2C000,beforepeoplebegantodrastically
8. Peterson L, van Asselt H. Assessing risks to the implementation of NDCs under the Paris Agreement. Clim Policy. 2026;26:462-476. Available from: https://doi.org/10.1080/14693062.2025.2513023
9. Harishma KM, Sandeep S, Sreekumar VP. Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast of India. Ecol Process. 2020;9:31. Available from: https://doi.org/10.1186/s13717-020-00227-8
10. Roy S. Distributions of phytoplankton carbohydrate, protein and lipid in the world oceans from satellite ocean colour. ISME J. 2018;12:1457-1472. Available from: https://doi.org/10.1038/s41396-018-0054-8
11. Divya M, Kumar SD, Krishnaveni N, Santhanam P. A study of carbon sequestration by phytoplankton. In: Santhanam P, Begum A, Pachiappan P, editors. Basic and Applied Phytoplankton Biology. Singapore: Springer; 2018. p. 277-284. Available from: https://doi.org/10.1007/978-981-10-7938-2_15
12. Shimakawa G, Demulder M, Flori S, Kawamoto A, Tsuji Y, Nawaly H, et al. Diatom pyrenoids are encased in a protein shell that enables efficient CO_2 fixation. Cell. 2024;187:5919-5934. Available from: https://doi.org/10.1016/j.cell.2024.09.013
13. Behrenfeld MJ. Climate-mediated dance of the plankton. Nat Clim Chang. 2014;4:880-887. Available from: https://doi.org/10.1038/nclimate2349
14. N'Yeurt AR, Chynoweth DP, Capron ME, Stewart JR, Hasan MA. Negative carbon via ocean afforestation. Process Saf Environ Prot. 2012;90:467-474. Available from: https://doi.org/10.1016/j.psep.2012.10.008
15. Viswanathan C, Purvaja R, Jeevamani JJJ, Samuel VD, Sankar R, Abhilash KR, et al. Salt marsh vegetation in India: species composition, distribution, zonation pattern and conservation implications. Estuar Coast Shelf Sci. 2020;242:106792. Available from: https://doi.org/10.1016/j.ecss.2020.106792
16. Mishra AK, Acharya P, Apte D, Farooq SH. Seagrass ecosystem adjacent to mangroves store higher amount of organic carbon of Andaman and Nicobar Islands, Andaman Sea. Mar Pollut Bull. 2023;193:115135. Available from: https://doi.org/10.1016/j.marpolbul.2023.115135
17. Austin WEN, Kumar VV, Pathak M, Parihar S, Houston A, Apine E, et al. Priority setting of India's blue carbon ecosystems as nature-based solutions for climate, people and biodiversity. R Soc Open Sci. 2026;13:252380. Available from: https://doi.org/10.1098/rsos.252380
18. Akhand A, Chanda A, Jameel Y, Dasgupta R. The present state-of-the-art of blue carbon repository in India: a meta-analysis. Sustain Sci. 2023;18:1031-1042. Available from: https://doi.org/10.1007/s11625-022-01181-4
19. Choudhary B, Dhar V, Pawase AS. Blue carbon and the role of mangroves in carbon sequestration: mechanisms, estimation, human impacts and conservation strategies. J Sea Res. 2024;199:102504. Available from: https://doi.org/10.1016/j.seares.2024.102504
20. McKenzie LJ, Nordlund LM, Jones BL, Cullen-Unsworth LC, Roelfsema C, Unsworth RKF. The global distribution of seagrass meadows. Environ Res Lett. 2020;15:074041. Available from: https://doi.org/10.1088/1748-9326/ab7d06
21. Bourgoin C, Verhegghen A, Carboni S, Ameztoy I, Degreve L, Fritz S, et al. GFC2020: a global map of forest land use for year 2020 to support the EU Deforestation Regulation. Earth Syst Sci Data. 2026;18:1331-1365. Available from: https://doi.org/10.5194/essd-18-1331-2026
22. Mossman HL, Pontee N, Born K, Hill C, Lawrence PJ, Rae S, et al. Rapid carbon accumulation at a saltmarsh restored by managed realignment exceeded carbon emitted in direct site construction. PLoS One. 2022;17:e0259033. Available from: https://doi.org/10.1371/journal.pone.0259033
23. Stankovic M, Mishra AK, Rahayu YP, Lefcheck J, Murdiyarso D, Friess DA, et al. Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia. Sci Total Environ. 2023;904:166618. Available from: https://doi.org/10.1016/j.scitotenv.2023.166618
24. Pickerell T, Ashford OS. Ocean-based solutions can help close the climate emissions gap. Sustainability. 2025;17:7951. Available from: https://doi.org/10.3390/su17177951
25. Roy M, Akbar D. The blue nexus unveiled: interlinking marine pollution, circular economy and the blue economy. Mar Pollut Bull. 2025;223:119028. Available from: https://doi.org/10.1016/j.marpolbul.2025.119028
26. International Maritime Organization. International Convention for the Prevention of Pollution from Ships (MARPOL) [Internet]. 2025 [cited 2025 Jul 15]. Available from: https://www.imo.org/en/about/conventions/pages/international-convention-for-the-prevention-of-pollution-from-ships-(marpol).aspx
27. United Nations. Overview: Convention & Related Agreements [Internet]. 2025 [cited 2025 Jul]. Available from: https://www.un.org/depts/los/convention_agreements/convention_overview_convention.htm
28. UNFCCC. India Updated First Nationally Determined Contribution [Internet]. 2022 [cited 2025 Jul 25]. Available from: https://unfccc.int/documents/611410
29. UNFCCC. Nationally determined contributions under the Paris Agreement: synthesis report by the secretariat [Internet]. 2024 [cited 2025 Jul 26]. Available from: https://unfccc.int/sites/default/files/resource/20241025_ar_draft.pdf
30. UNFCCC. Seychelles First NDC (updated submission) [Internet]. 2022 [cited 2025 Jul 29]. Available from: https://unfccc.int/documents/497964
31. UNFCCC. Mexico: Updated NDC 2022 [Internet]. 2022 [cited 2025 Jul 29]. Available from: https://unfccc.int/documents/624282

32. UNFCCC. Costa Rica First NDC (updated submission) [Internet]. 2020 [cited 2025 Jul 29]. Available from: https://unfccc.int/documents/497449

33. UNFCCC. Belize First NDC (updated submission) [Internet]. 2022 [cited 2025 Jul 29]. Available from: https://unfccc.int/documents/497163

34. Robinet F. UN ocean summit in Nice closes with wave of commitments. UN News. 2025. Available from: https://news.un.org/en/story/2025/06/1164381

35. United Nations Environment Programme. World must act faster to protect 30% of the planet by 2030 [Internet]. 2024 [cited 2025 Aug 4]. Available from: https://www.unep.org/news-and-stories/press-release/world-must-act-faster-protect-30-planet-2030

36. Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, Landschutzer P, et al. Global Carbon Budget 2024. Earth Syst Sci Data. 2025;17:965-1039. Available from: https://doi.org/10.5194/essd-17-965-2025

37. Dutkiewicz S, Morris JJ, Follows MJ, Scott J, Levitan O, Dyhrman ST, et al. Impact of ocean acidification on the structure of future phytoplankton communities. Nat Clim Chang. 2015;5:1002-1006. Available from: https://doi.org/10.1038/nclimate2722

38. Dai R, Wen Z, Hong H, Browning TJ, Hu X, Chen Z, et al. Eukaryotic phytoplankton drive a decrease in primary production in response to elevated CO_2. Proc Natl Acad Sci U S A. 2025;122:e2423680122.Available from: https://doi.org/10.1073/pnas.2423680122

39. UNFCCC. Plenty of Fish? How overfishing harms the climate [Internet]. 2022 [cited 2025 Aug 5]. Available from: https://unfccc.int/news/plenty-of-fish

40. National Geographic. Scientists uncover new marine source of carbon emissions into atmosphere. 2024. Available from: https://news.nationalgeographic.org/scientists-uncover-new-marine-source-of-carbon-emissions-into-atmosphere-finding-bottom-trawling-contributes-to-global-warming/

41. Menendez P, Losada IJ, Torres-Ortega S, Narayan S, Beck MW. The global flood protection benefits of mangroves. Sci Rep. 2020;10:4404. Available from: https://doi.org/10.1038/s41598-020-61136-6

42. Li Z, England MH, Groeskamp S. Recent acceleration in global ocean heat accumulation by mode and intermediate waters. Nat Commun. 2023;14:6888. Available from: https://doi.org/10.1038/s41467-023-42468-z

43. Bilgili M. Trend in global ocean heat content into different depth layers from 1940 to 2050. Nat Hazards. 2025;121:12215-12242. Available from: https://doi.org/10.1007/s11069-025-07278-0

44. Sala E, Mayorga J, Bradley D, Cabral RB, Atwood TB, Auber A, et al. Protecting the global ocean for biodiversity, food and climate. Nature. 2021;592:397-402. Available from: https://doi.org/10.1038/s41586-021-03371-z

45. Press Information Bureau. Where the land meets the sea: mangroves as guardians of life and livelihoods [Internet]. 2025. Available from: https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/apr/doc202541530201.pdf

46. CSIR-NIScPR. Extension bulletin on seagrasses: the oxygen pumps in the sea [Internet]. 2023. Available from: https://niscpr.res.in/includes/images/wealthofindia/WoI-Extension-Bulletin-Seagrasses-Jan13.pdf

47. Balakrishnan VS. The true cost of bottom trawling in Europe. Lancet Planet Health. 2025;9:101270. Available from: https://doi.org/10.1016/S2542-5196(25)00134-2

48. Mehta A. Sea change needed at global talks to save ocean from disaster. Reuters. 2025 Jun 3. Available from: https://www.reuters.com/sustainability/land-use-biodiversity/sea-change-needed-global-talks-save-ocean-disaster-2025-06-03/

49. Press Information Bureau. Parliament Question: Blue Carbon Project [Internet]. 2025. Available from: https://www.pib.gov.in/PressReleasePage.aspx?PRID=2152126

50. Viswanathan C, Jeevamani JJJ, Abhilash KR, Amrutha PA, Balachandar K, Manodheepan KK, et al. Structural development and ecological services of restored mangroves in Adyar Estuary, India. Nord J Bot. 2025;2025:e04562. Available from: https://doi.org/10.1111/njb.04562

51. Fest BJ, Swearer SE, Arndt SK. A review of sediment carbon sampling methods in mangroves and their broader impacts on stock estimates. Sci Total Environ. 2022;816:151618. Available from: https://doi.org/10.1016/j.scitotenv.2021.151618

52. Gomis E, Strydom S, Foster NR, Montemayor D, Mateo MA, Serrano E, et al. Global estimates of seagrass blue carbon stocks in biomass and net primary production. Nat Commun. 2025;16:9530. Available from: https://doi.org/10.1038/s41467-025-64667-6

53. Hilmi N, Chami R, Sutherland MD, Hall-Spencer JM, Lebleu L, Benitez MB, Vevin LA. The role of blue carbon in climate change mitigation and carbon stock conservation. Front Clim. 2021;3:710546. Available from: https://doi.org/10.3389/fclim.2021.710546

54. Maddi BR, Parkhe SS, Kamble JD, Shelake RS, Sawant PA, Galate AS. Blockchain-based blue carbon registry and MRV system. Int J Adv Res Sci Commun Technol. 2025;5:661-681. Available from: https://doi.org/10.48175/IJARSCT-29386

55. Nolan C, Van Paasschen CA, Field CB. Additionality, baselines, and the proper accounting for land-based climate change mitigation efforts. Oxf Open Clim Change. 2024;4:kgae012. Available from: https://doi.org/10.1093/oxfclm/kgae012

56. Dahl M, Lavery PS, Mazarrasa I, Samper-Villarreal J, Adame MF, Crooks S, et al. Recommendations for strengthening blue carbon science. One Earth. 2025;8:101175. Available from: https://doi.org/10.1016/j.oneear.2025.101175

57. Singh A, Kumar R, Lakhchaura P, Pandey K, Ghosh S, Yadav S. Estimation of carbon stock in mangrove ecosystem [Internet]. Dehradun: Forest Survey of India; 2023. Available from: https://fsi.nic.in/uploads/documents/Mangrove%20Carbon%20Report.pdf

58. UNFCCC. India Biennial Update Report (BUR4) [Internet]. 2024. Available from: https://unfccc.int/documents/645149

59. Nag J. Sundarbans has lost 110 square kilometres of mangroves in two decades. Econ Times. 2023. Available from: https://economictimes.indiatimes.com/news/india/sundarbans-has-lost-110-square-kilometres-of-mangroves-in-two-decades/articleshow/97260589.cms

60. Times of India. In Kerala, mangrove trees make way for booming city of Kochi. Times of India. 2023. Available from: https://timesofindia.indiatimes.com/india/in-kerala-mangrove-trees-make-way-for-booming-city-of-kochi/articleshow/99310189.cms

61. Antony S, Perumal K, Devi SS, Shahajan S, Kumar AB. Exploring blue carbon research in India: current landscape and future avenues. Mar Pollut Bull. 2025;219:118269. Available from: https://doi.org/10.1016/j.marpolbul.2025.118269

62. Pandey A. The missing piece: blue carbon in India's voluntary carbon market [Internet]. Observer Research Foundation; 2025 [cited 2025 Aug 25]. Available from: https://www.orfonline.org/expert-speak/the-missing-piece-blue-carbon-in-india-s-voluntary-carbon-market