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Review Article

Blue carbon sequestration in seagrass ecosystems: A global synthesis with an emphasis on India's situation, difficulties and possibilities

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Blue carbon ecosystems consisting of seagrass meadows, mangroves and salt marshes play a major role in mitigating climate change through long-term carbon sequestration. Among these ecosystems, seagrass meadows are increasingly recognised for their carbon storage potential, but so far remain underrepresented in global carbon accounting efforts, particularly in developing nations like India. India's seagrass habitats spanning approximately 500 km^2, particularly in Palk Bay, the Gulf of Mannar, and the Andaman and Nicobar Islands, are highly vulnerable to anthropogenic disturbances and environmental changes, with annual losses ranging from 0.7 to 7 %. The blue carbon potential of Indian seagrass is inadequately defined compared to mangroves; nevertheless, estimates suggest that its storage is approximately 6.7 TgC. This review combines the global and Indian literature on seagrass blue carbon dynamics, assessing biomass, sedimentary carbon storage, and region-wise sequestration capacities. It highlights the key environmental drivers, such as hydrodynamics and nutrient availability, as well as anthropogenic impacts that affect the carbon storage. It also identifies the methodological inconsistencies and critical research gaps that impede the integration of seagrass blue carbon into national policy frameworks. These gaps are addressed to strengthen India's role in global climate mitigation, blue carbon credit systems, and to promote ecosystem-based coastal management.

[**Keywords**: Blue Carbon, Carbon sequestration, Climate change mitigation, Environmental drivers, Indian coasts, Seagrass]

Introduction

The term 'Blue Carbon' denotes that the carbon sequestered and retained by coastal and marine environments, particularly seagrass meadows, salt marshes and mangroves[1]. These blue carbon ecosystems are recognised for their extraordinary capacity to sequester atmospheric CO_2, with global estimates representing around 30,000 TgC stored across these habitats. Though mangroves and salt marshes have received considerable research attention, seagrass ecosystems are scientifically underexplored due to several challenges, including their submerged nature, patchy distribution, species-specific variability, difficulty with remote sensing, and challenges of long-term in situ monitoring. These factors complicate accurate mapping, biomass estimation, and carbon stock assessments in seagrass meadows.

As reported by Pang *et al*.[2], the progress of the 2030 Agenda for Sustainable Development is currently at the midpoint, with merely 15 % of the global objectives successfully attained. This bibliometric analysis underscores the increasing significance of blue carbon ecosystems, including seagrasses, mangroves, and salt marshes, in mitigating climate change and advancing the Sustainable Development Goals (SDGs). It has been observed that research linking blue carbon to sustainable development remains fragmented, despite its considerable potential for long-term carbon storage and for enhancing coastal resilience. The literature from 2012 to 2023 was systematically reviewed to address this gap by visualising global research trends and identifying key themes, knowledge clusters, and prospective directions for the integration of blue carbon and sustainability[2].

In the Indian context, this knowledge gap is even more pronounced. Since there is little information on seagrass blue carbon in India compared to mangroves, quantifying blue carbon and maximising its potential are essential for the development of a sustainable nation. India is committed to reducing carbon emissions under the Paris Agreement. To achieve these targets, quantification of blue carbon helps assess the role of coastal ecosystems[3,4]. Seagrass meadows in India are predominantly located in the Palk Bay, Gulf of Mannar, Chilika Lagoon, Andaman and Nicobar Islands, and several additional coastal areas, which play a crucial role in carbon sequestration, but are inadequately represented in national climate policy frameworks. The Indian River Lagoon region encompasses roughly 40,000 hectares of seagrass habitat[5]. Accurate estimates of blue carbon potential of India and the surrounding region support conservation policies, blue carbon credits, and ecosystem-based management strategies[6]. This requires accounting for the studies on seagrass biomass, sedimentary carbon storage, and environmental drivers affecting sequestration potential by evaluating regional and global datasets and comparing carbon sequestration trends by compiling data from peer-reviewed publications. The key ideas of this review are to identify critical knowledge gaps in sequestration dynamics, methodological inconsistencies, and the influence of environmental factors such as hydrodynamics and nutrient fluxes in the seagrass ecosystem. By systematically addressing these research gaps, it is possible to enhance India's contribution to global climate mitigation efforts while concurrently ensuring the resilience of marine biodiversity and the sustainability of coastal livelihoods. This review integrates findings from research worldwide, including India, focusing on the carbon storage potential of seagrass, the environmental variables that affect this process, and the observed spatial variability. The results are expected to guide subsequent research initiatives and influence policy formulation. The implementation of conservation policies and the integration of seagrass habitats into blue carbon strategies are critical for achieving sustainable coastal management and ensuring long-term resilience. Additionally, identifying the research gaps in carbon sequestration dynamics may strengthen India's contribution to global climate mitigation efforts, thereby promoting the sustainability of marine biodiversity and coastal livelihoods.

Methodology

This review employed a systematic literature review methodology to gather, analyse, and synthesise data regarding seagrass blue carbon sequestration on a global scale and specifically within India. A thorough investigation was performed using major scientific databases, including Scopus, Web of Science, and Google Scholar. The search strategy employed a predefined set of keywords such as: “seagrass”, “blue carbon”, “carbon sequestration”, “Carbon stock”, “India”, “above ground biomass”, AND “below ground biomass” to capture studies addressing both Indian and global perspectives on seagrass blue carbon dynamics. Research articles published till January 2026 were evaluated for potential inclusion in this analysis. The papers were selected based on their relevance to the topics of seagrass carbon storage, sediment carbon evaluations, biomass quantification, and the environmental factors that influence these processes. To ensure scientific rigour, the grey literature, reports, and non-peer-reviewed articles were excluded. From an initial collection of 188 records, 121 pertinent studies were shortlisted following title and abstract screening and subsequent full-text assessment. Among these, 59 studies focusing specifically on Indian seagrass ecosystems were identified and subjected to detailed qualitative analysis regarding blue carbon (Appendix S1). Bibliographic data were compiled from Google Scholar and Scopus using the VOSviewer software to visualise the keyword co-occurrence networks (Fig. 1).

Results

Global blue carbon sequestration potential of seagrass

Seagrass ecosystems cover an estimated 8.3 to 25.4 million hectares globally, representing the largest restoration potential among coastal blue carbon ecosystems (Table 1). In comparison, mangroves contribute 9 to 13 million hectares, and tidal marshes occupy between 0.2 and 3.2 million hectares[7]. The combined annual global carbon sequestration potential of seagrass (43.9 MtC yr^{-1}), mangroves (24 MtC yr^{-1}), and salt marshes (13.4 MtC yr^{-1}) amounts to approximately 81.2 MtC yr^{-1} [ref. 8]. Seagrass meadows, which cover an area of 1,60,387 km^2 globally, have enormous potential for sequestering blue carbon by absorbing and retaining carbon in marine ecosystems[9]. Globally, organic carbon (Corg) stored in seagrass sediments is estimated to range up to 19.9 petagrams (Pg), with conservative values between 4.2–8.4 Pg[ref. 10]. Countries such as Australia, the United States, and Indonesia collectively account for 10.6 MtC yr^{-1}, underscoring the importance of coastal length and Exclusive Economic Zones (EEZs) in determining sequestration capacity.

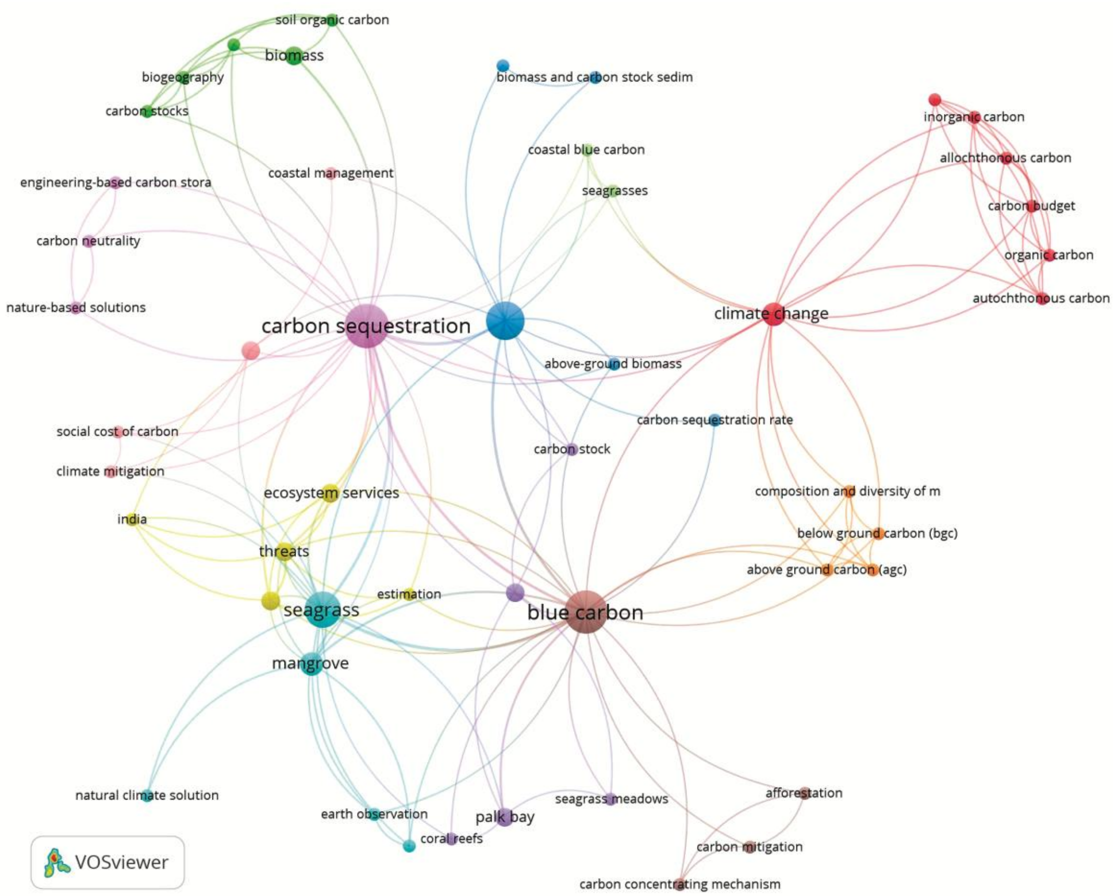

Fig. 1 — Network visualisation of keyword co-occurrence in blue carbon related literature

Table 1 — Global blue carbon stocks and sequestration rates in seagrass ecosystems

Sr. No.	Global blue carbon data	References
1	Global distribution of seagrass area range: 160387 – 266562 sq km	McKenzie *et al*., 2020(ref. 9)
2	Estimated global blue carbon area of seagrass meadows range: 8.3 – 25.4 million ha	Macreadie *et al*., 2021(ref. 7)
3	Annual carbon sequestration potential: 43.9±12.1 MtC yr^{-1} for seagrass	Bertram *et al.*, 2021(ref. 8)
4	Seagrass global carbon storage potential: 4.2 – 8.4 Pg carbon	Fourqurean *et al.*, 2012(ref. 38)
5	Global carbon burial rates in seagrass meadows : 48 – 112 Tg yr^{-1}	Kennedy *et al.*, 2010(ref. 90)
6	Sediment inorganic carbon (SIC) range between 1.53 and 203.17 Mg C ha^{-1}	Ren *et al.*, 2025(ref. 92)
7	Seagrass epibiont sediment Maldives, is 853,000 kg $CaCO_3$ yr^{-1} 1.1 km^2	East *et al.*, 2023(ref. 91)
8	Western Indian Ocean's sedimentary organic carbon (Corg) is 0.20 % – 1.44 %	Gullström *et al.*, 2018(ref. 94)
9	In Indonesia, sedimentary Corg stocks vary between 11.9 and 32.1 Mg C ha^{-1}	Rahayu *et al.*, 2019(ref. 105)
10	Colombian Caribbean stored 241±118 Mg Corg ha^{-1} in the top 1 m of soil	Serrano *et al.*, 2019(ref. 11)

Quantitative estimates of Corg storage across different global regions demonstrate the massive sequestration capacity of seagrasses (Fig. 2). Australia has the largest known seagrass coverage globally, ranging between 9.26 to 12.77 million hectares, with an average Corg storage of 112±88 Mg ha^{-1}, contributing a 906.5 Tg of Corg stock[11]. This emphasises that Australia has a dominant role in global seagrass blue carbon storage, owing to its vast coastline and diverse meadows. Southeast Asia, based on this study, has approximately 3.66 million hectares of seagrass with an average Corg storage of 121.95±76.11 Mg ha^{-1}, amounting to 429 Tg of Corg stock. These figures emphasise the importance of tropical seagrass ecosystems in blue carbon dynamics, particularly in regions with high biodiversity and rapid coastal change.

West Africa also represents a critical blue carbon hotspot, with 4.83 million hectares of seagrass storing 139.2 Mg ha^{-1}, totalling 673 Tg of Corg.

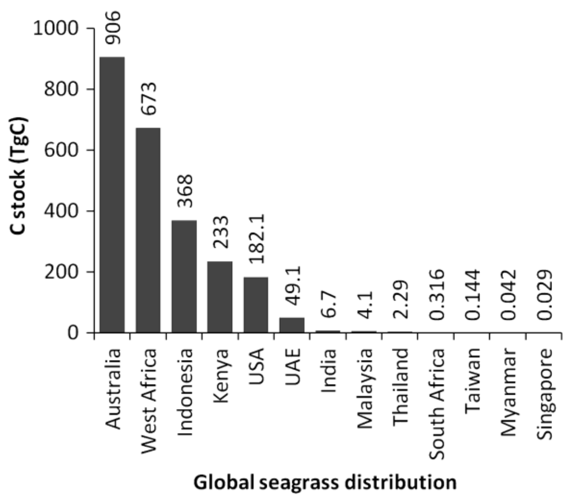

Fig. 2 — Distribution of the global seagrass carbon stock (Tg C) in various countries

The West African region's total carbon storage is 1830 Tg, of which 854 Tg (47 %) comes from mangroves, 673 Tg (37 %) from seagrasses, and 303 Tg (17 %) from salt marshes[12]. The averages of West African seagrass organic and inorganic carbon stock ranged from 24.68 to 111.52 MgC ha^{-1}, indicating a substantial intra- and inter-country variation that is below the global average[13].

South African seagrass *Zostera capensis* stores roughly 2.39 MgC ha^{-1} in biomass, which is comparable to the global average[14]. Their top 1 m of sediment has a lower organic carbon concentration than the global average, at about 177.65 MgC ha^{-1}. Estuaries differed in their capacity to store carbon, with the Swartkops Estuary in South Africa having the highest quantities because of wastewater outflow. Overall, the 1755 hectares of the endangered *Z. capensis* seagrass ecosystem in South Africa can store roughly 315970 Mg of carbon, which helps regulate the climate. A few Asian nations have a far greater diversity of seagrass species than African nations and open ocean island nations[15]. There are still many unanswered questions about the distribution of seagrass beds, even though Southeast Asia is a major region for seagrass diversity worldwide.

The high storage values emphasise the ecosystem services provided by these meadows, despite often being overlooked in conservation policies. In the Gulf of Mexico (USA), about 947,327 hectares of seagrass contain 170 Mg ha^{-1} of Corg, resulting in a total Corg stock of 182.1 Tg[ref. 16]. This dense carbon repository highlights the ecological importance of subtropical meadows in the northern Gulf. The North Pacific coast, even though relatively small in extent (47,400 ha), still contributes 1.2 Tg of Corg stock, demonstrating that even modest seagrass areas can play a role in blue carbon sequestration. Further, seagrass ecosystems contribute enormously to global blue carbon wealth, with an estimated annual economic value of US$190 billion. Australia is the largest contributor, accounting for US$25 billion annually. This economic value stems from the diverse ecosystem services provided by seagrasses, namely shoreline protection, nutrient cycling, and habitat support for marine biodiversity.

The carbon sequestration potential of seagrass meadows varies based on species composition, environmental conditions, and geographic location. For example, species like *Syringodium isoetifolium*, *Cymodocea serrulata*, and *Enhalus acoroides* play a substantial role in carbon accumulation[8]. Under nutrient-enrichment scenarios, seagrasses exhibit varied nutrient absorption efficiencies and carbon content depending on the species involved[17,18].

Spatial variation in sediment carbon content is evident in estuarine and coastal systems. For instance, along central Queensland's estuarine zones in northeastern Australia, seagrass-dominated sites in upper estuary regions contained up to 52.16 mg Corg cm^{-3}. In contrast, those near the estuary mouth had as little as 1.06 mg Corg cm^{-3}[ref. 19]. In the Balearic Islands of the Mediterranean Sea, satellite imagery (Sentinel-2 A/B) revealed 505.6 km² of seagrass meadows at depths up to 30 meters, storing approximately 12.27 million Mg Corg[20]. These data illustrate the spatial variability and depth tolerance of seagrass, both of which influence global estimates of carbon storage. Due to their ability to sequester and store carbon at rates comparable to or exceeding those of terrestrial forests, seagrasses play a crucial role in climate change mitigation[21,22]. However, nutrient enrichment can modify their biochemical composition, affecting herbivory, community structure, and the proportion of refractory (long-lived) carbon stored in sediments[23-27].

Seagrass coverage varies greatly among Asian nations: India (516.6 km^2), the United Arab Emirates (5,500 km^2), and Indonesia (8,813 km^2) all record sizable areas[28]. Many areas, including Bangladesh, Oman, and Pakistan, lack thorough data on the distribution of seagrasses despite their ecological significance. Seagrass ecosystems across the Middle East countries, including relatively underdocumented regions like the Arabian Gulf, contribute significantly to blue carbon sequestration. In Abu Dhabi (UAE), seagrass meadows dominated by *Halodule uninervis*, *Halophila ovalis,* and *H. stipulacea* had modest per-hectare carbon stocks but high cumulative storage due to their widespread distribution. While biomass carbon averaged to 0.4 Mg C ha^{-1}, the soil organic carbon reached up to 109 Mg C ha^{-1}. Overall, 400 Gg C is stored in living biomass and 49.1 Tg C in soils. These findings can support the global importance of preserving diverse seagrass habitats to sustain their carbon sink function[29].

According to recent modelling data, Indonesia's vast seagrass meadows are estimated to be 18,868 km^2, making it a significant contributor to blue carbon storage. Thailand, Malaysia, and Iran also have significant potential for carbon sequestration with 1873 km^2, 545 km^2, and 3515 km^2, respectively[30,31]. Effective conservation and management initiatives are not materialised due to the absence of data for several coastal countries. Prior research on the metabolism of seagrass communities in the Indo-Pacific, Africa, and South America in relation to carbon dynamics was severely lacking[32]. In a seagrass meadow in Southeast Asia, partial pressure of CO_2 (pCO_2) and dissolved oxygen (DO) measurements were particularly highlighted in a number of reports. These reports also included metabolic rates, *i.e*. gross primary production (GPP), community respiration (CR), and net community production (NCP)[33-35].

The average Corg storage in Southeast Asia is estimated as 121.95 Mg C ha^{-1}. Less than 3 % of Corg is found in biomass, compared to over 97 % in sediment, which is five times higher than the value previously recorded in the Indo-Pacific region. The Andaman and Nicobar Islands (ANI) of India had the highest sequestration potential (184.24 Mg per hectare). Vietnam (133.16 Mg C ha^{-1}), Thailand (134.20 Mg C ha^{-1}), and Myanmar (136.67 Mg C ha^{-1}) are the second-highest. Malaysia (108.63 Mg per hectare) and the Philippines had the lowest (123.49 Mg ha^{-1}) sequestration potential. Conversely, carbon stock storage in Indonesia is 368 TgC, which is a greater amount than the global scale[36]. The total seagrass area in these countries is approximately 3.66 million hectares based on biomass. About 6 to 12 % of the estimated 30 to 60 million hectares of seagrass cover worldwide are made up of this[37,38]. In Taiwan, the dominant intertidal seagrass species have been found to sequester carbon at rates ranging from 2.93 to 6.22 Mg C per hectare per year with carbon stocks between 8.91 and 10.50 Mg C ha^{-1}. Altogether, the total carbon stored in Taiwan's seagrass beds is estimated at 144,444 Mg of carbon[39]. In China, the average organic carbon (Corg) stocks in living seagrass biomass and sediments were 0.04±0.01 Mg C ha^{-1} and 42.03±25.07 Mg C ha^{-1}, respectively. These values are significantly lower than the global averages, which are 2.52±0.48 Mg C ha^{-1} for biomass and 194.2 Mg C ha^{-1} for sediments[40]. Global seagrass distribution data have not been uploaded to the UNEP-WCMC global seagrass database since 2000[ref. 41], despite the fact that seagrasses have been the subject of intensive research in many locations. Seagrass can help maintain the global carbon balance by absorbing CO_2 from the atmosphere, which can be achieved by supporting conservation efforts.

Blue carbon and seagrass ecosystem in India

The length of the Indian coastline has grown from 7,516 to 11,098 kilometres. With a coastline length rising from 906 to 1,068 km, Tamil Nadu has surpassed Andhra Pradesh to become the state with the second-longest coastline in India[39] providing a chance to expand India's blue carbon ecosystem (Fig. 3). Larger mangrove forests can be found in India's Sundarbans, which span 4200 square kilometre in Indian divisions and 6,000 square kilometres in Bangladesh divisions. The Indian Sundarbans Mangrove Restoration project aimed to plant 6000 ha of mangroves over three years to increase biodiversity conservation, reduce carbon emissions, and mitigate climate change. The mangrove biomass and soil are expected to store an estimated 7,00,000 tonnes of carbon over a 20-year period[42]. Even though the Sundarbans are home to the world's largest estuarine mangrove forest, over 28 % of its area has been lost in the last 40 years due to sea level rise brought on by climate change[43]. Salt marshes are essential coastal habitats because of their great capacity to sequester carbon. Both Above Ground Biomass (AGB) and Below Ground Biomass (BGB) are used to store carbon. In India, salt marshes' AGB carbon ranges from 0.05 to 14.87 Mg C ha^{-1}, whereas BGB carbon ranges from 0.009 to 4.49 Mg C ha^{-1}. Their soils are significant carbon sinks with recorded values up to 54.46 Mg C ha^{-1}. Along coastlines such as Gujarat, the Sundarbans, and Tamil Nadu, these ecosystems play a crucial role in mitigating the effects of climate change[44]. However, it faces threats from land-use changes, pollution, and rising sea levels[45].

Around 500 km^2 of seagrass can be found in India, primarily in Palk Bay, the Gulf of Mannar, the Andaman and Nicobar Islands (Fig. 4)[46-48,62], the

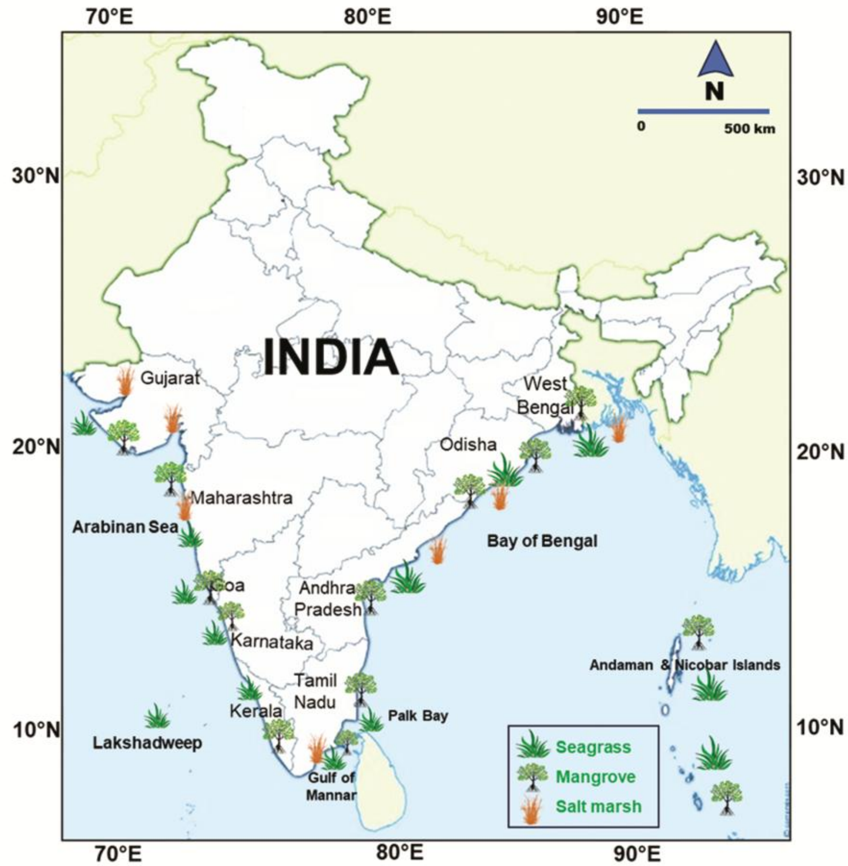

Fig. 3 — Map showing the blue carbon hotspots along the Indian coastline

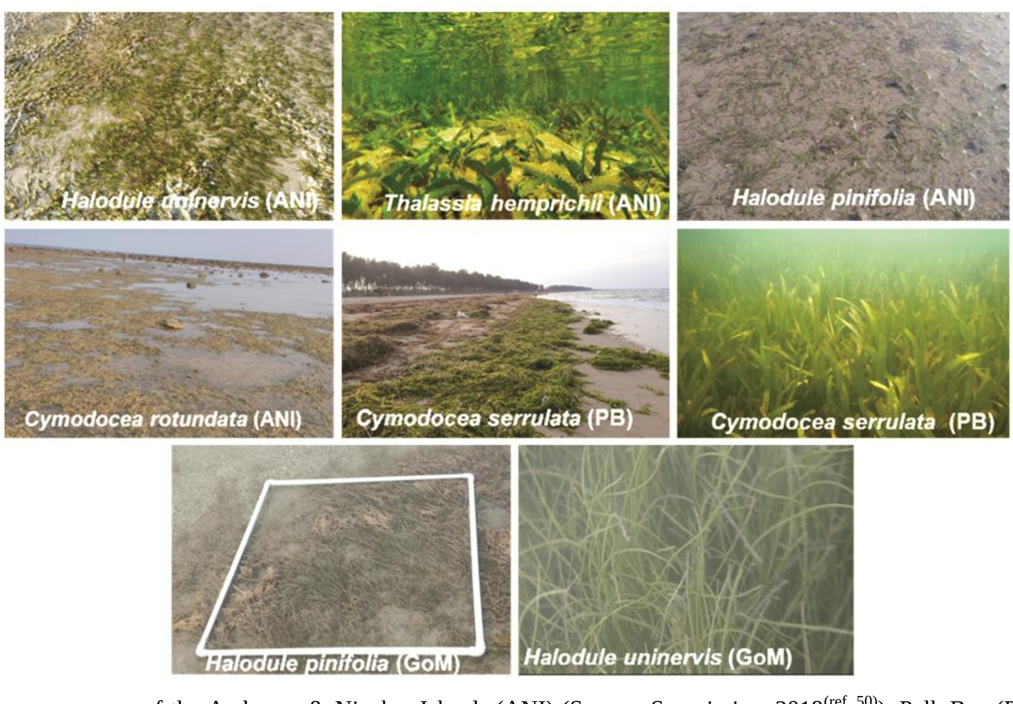

Fig. 4 — Common seagrasses of the Andaman & Nicobar Islands (ANI) (Source: Savurirajan, 2018[ref. 50]), Palk Bay (PB), and Gulf of Mannar (GoM))

Table 2 — Carbon stocks and sequestration rates in Indian seagrass ecosystems

Distribution	Seagrass sp.	Extent cover (sq.km)	Biomass (Mg ha⁻¹)	C Seq potential (Mg C)	References
Palk Bay (Tamil Nadu)	14	329.70	11.44	43996	Geevarghese *et al*., 2018(ref. 62); Kaladharan *et al*., 2020(ref. 71);
Gulf of Mannar, (Tamil Nadu)	14	69.11	0.78	1782	Kaladharan *et al*., 2020(ref. 71) Thangaradjou & Bhatt 2018 (ref. 55)
Chilika Lagoon, (Odisha)	05	85.47	6.90	5700	Singh *et al.*, 2015(ref. 106); Kaladharan *et al.*, 2021(ref. 52)
Pulicat Lake (Andhra Pradesh)	04	32	1.43 – 11.4	0.49 – 9.52	Murugan *et al.*, 2024(ref. 89); Kaladharan *et al.*, 2021(ref. 52)
Gulf of Kutch (Gujarat)	08	23	--	--	Anand *et al.*, 2024(ref. 54); Adhavan *et al.*, 2022(ref. 53)
Andaman and Nicobar Islands	11	29.3	--	988	Gole *et al.*, 2024(ref. 107); Mishra *et al.*, 2023(ref. 21)
Lakshadweep Islands	07	0.72	--	0.9795	Kaladharan *et al.*, 2021(ref. 52)
Overall estimates	16	516.59	0.2 – 2.90 MgC ha^{-1}	6.7 Tg C	Ganguly *et al.*, 2018(ref. 59); Chanda *et al.*, 2022(ref. 15)

Lakshadweep Islands, and the Gulf of Kutch[49-50]. Totally 16 species of seagrass are available in India: Cr (*Cymodocea rotundata*); Cs (*Cymodocea serrulata*); Ea (*Enhalus acoroides*); Hb (*Halophila beccarii*); Hp (*Halodule pinifolia*); Hu (*Halodule uninervis*); Hw (*Halodule wrightii*); Hd (*Halophila decipiens*); Hm (*Halophila minor*); Ho (*Halophila ovalis*); Hov (*Halophila ovata*); Hs (*Halophila stipulacea*); Rm (*Ruppia maritima*); Si (*Syringodium isoetifolium*); Th (*Thalassia hemprichii*); and Tt (*T. testudinum)*. Out of which, the Gulf of Mannar and Palk Bay have 14 species each. Palk Bay is an important location for seagrass ecosystems, with soil carbon stock of 129 Mg C ha^{-1} at the top 1 m of soil. In India, the largest seagrass meadows are found in the Gulf of Mannar-Palk Bay region (~400 km^2), followed by Chilika Lagoon (169.2 km^2) and Gulf of Kutch (23 sq. km). The blue carbon stock in the top 30 cm of seagrass habitats in Chilika Lagoon at 2.02±0.67 MgC per hectare[51-54]. The Soil Organic Carbon pool was 40 times larger than the seagrass biomass, and the organic carbon concentration decreased with depth (0.012 % per cm)[55-56]. When multiplied by the projected total seagrass coverage for India (Table 2), the result is that the seagrass beds in India contain roughly 6.7 Tg C (Fig. 5)[57]. Totally, 13 species of seagrass are present, covering a sprawl of 175 km^2 in the Palk Bay[58-60]. There were 399 km^2 of seagrass cover overall in the Gulf of Mannar and Palk Bay[61]. *Halophila stipulacea* was the least prominent among the seagrass species, while *Cymodocea serrulata* accounted for 37 % of the total. Satellite data estimated an area of 85.5 sq km of seagrass beds

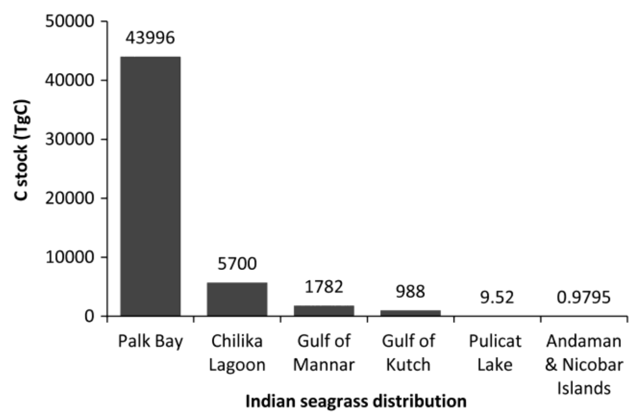

Fig. 5 — Indian seagrass carbon stock (MgC) across various regions along the East and West coasts of India

in the Gulf of Mannar in addition to the previously mentioned reports[62]. On some islands in the Gulf of Mannar, restoration efforts have been undertaken to increase seagrass cover in the degraded seagrass area[63]. Due to a bigger seagrass cover and increased settling of organic matter and seagrass leaf litter, the Palk Bay region has been shown to have a higher soil carbon density than the Gulf of Mannar. Palk Bay's blue carbon stock was measured to be 0.043996 Tg C(ref. 64). Given their significance, it is imperative to evaluate the present condition and potential for carbon sequestration in blue carbon ecosystems, especially in Palk Bay regions, which may contain substantial potential, but very few attempts are made to study the blue carbon resources therein. Investigating the current state of Corg while seagrass meadows remain pristine is crucial, as recent findings indicate that the population trends of some seagrass species in the

Andaman Nicobar Islands (ANI) are declining due to increased anthropogenic pressure[65-67].

Global pressures and degradation threats

Despite their ecological value, seagrass ecosystems are under increasing threat from anthropogenic pressures. Over the past several decades, deforestation, coastal development, population growth, mariculture activities, sedimentation, and climate change have collectively contributed to the degradation of nearly one-third of global blue carbon ecosystems, with annual losses ranging from 0.7 to 7 %[(refs. 68-70)]. These threats also cause the release of 0.15 to 1.02 billion tons of carbon into the atmosphere each year, which exacerbates global warming. Environmental factors such as water temperature, salinity, turbidity and tidal patterns also strongly influence seagrass distribution, health, and carbon sequestration potential. Dense seagrass canopies are essential for reducing wave energy, trapping organic particles and supporting marine biodiversity.

Environmental factors affecting blue carbon

Blue carbon ecosystems are not only essential long-term carbon sinks but also help to mitigate climate change[6]. However, blue carbon sequestration and storage capacities are strongly influenced by environmental factors such as hydrology, sediment composition, and nutrient availability, as well as by human disturbances. There is a direct relationship between seagrass density, remineralisation, carbonate dissolution, and organic matter (Table 3)[71].

Hydrology and sedimentation

The relatively low seagrass cover on the seaward side is largely attributed to persistent strong waves[72]. Compared to Palk Bay, the Gulf of Mannar region has less dense seagrass cover, though it has clearer waters[73]. By controlling the deposition of organic matter and the storage of undersea sediments, hydrology and sedimentation patterns affect the storage of blue carbon. Estuaries and lagoons are examples of coastal wetlands with geomorphologic settings that show higher rates of organic carbon accumulation. Over a 32-year chronosequence, blue carbon accumulation rates ranged from 75 to 430 g C/m²/yr in a study of artificial coastal marshes[74]. Similarly, improved carbon burial rates above 200 Mg C/ha were associated with sedimentation rates of 2.3–3.8 mm/yr in mangrove ecosystems[75,76].

Biogeochemical factors

Soil chemistry and nutrient availability are important factors in the sequestration of organic carbon. Carbon stocks in seagrass meadows on the Korean Peninsula were affected by variation in muddy and sandy substrates; storage values ranged from 49 to 125 Mg C/ha[(refs. 77-79)]. Microbial decomposition and carbon stabilisation are further influenced by pH, SOC, C:N ratio, and soil organic matter levels. Microbial mediation in carbon sequestration is highlighted by the fact that microbial-derived residuals in mangroves can account for up to 45 % of total soil carbon stocks[80]. In Palk Bay, nutrient levels indirectly affect seagrass photosynthetic ability[81]. Over time, these stressors can weaken seagrass meadows' resilience, reducing their ability to sequester carbon and affecting their function as a vital blue carbon sink.

Climate change and ocean acidification

Blue carbon sequestration is hindered by ocean acidification and sea-level rise driven by climate change. Changes in seagrass production have been associated with rising sea temperatures and CO_2 levels, with species-specific differences impacting carbon dynamics. Variations in the oceanic and the atmospheric CO_2 concentrations across different regions of the ocean and throughout the year would also affect the rate of CO_2 drawdown driven by seaweeds' uptake of carbon[82]. Significant carbon loss in disturbed environments might result from reduced carbon sequestration effectiveness caused by soil type and tidal inundation period[83]. Unprotected seagrass meadow degradation could threaten climate change mitigation efforts by releasing stored carbon back into the atmosphere.

Land-use changes and anthropogenic impacts

Urbanisation and industrialisation are two land-use changes that have a significant impact on the storage of blue carbon. Over a 10-year period, industrialisation decreased blue carbon reserves by 25 % in Indonesia's Metropolitan Semarang's coastal areas[84]. Similarly, mangrove degradation due to the growth of aquaculture, particularly shrimp farming, has resulted in a 41 % loss of stored carbon in the impacted areas[85]. Carbon losses were reduced through integrated strategies, including sustainable aquaculture methods and mangrove restoration. Because of numerous human activities, seagrass habitats are extremely vulnerable. Dredging, trawl fishing, and industrial wastewater discharge endanger seagrass meadows[86].

Carbon sequestration variability in blue carbon ecosystems

Significant variation was observed when seagrass blue carbon storage at several study locations was

Table 3 — Environmental factors affecting blue carbon storage

Sr. No.	Environmental factors	Impact on blue carbon storage	References
1	Geomorphologies and storm events	Organic-rich sediments enhance carbon burial; disturbances lead to carbon loss; loss of 0.15 – 1.02 billion tons of carbon; 28 % of its land has been lost in the past 40 years from the effects of sea level rise in Sundarbans India	Mazarrasa *et al.*, 2021(ref. 77); Pendleton *et al.*, 2012(ref. 68); Dey & Kar, 2012(ref. 45)
2	Tidal influence, depth, wave and current direction	Regulates sediment deposition and organic matter input. Macroalgal deposit and total organic carbon affected	Abbott *et al.*, 2019(ref. 76); Erlania *et al.*, 2023(ref. 78)
3	Hydrology & sedimentation	Loss of saline wetlands due to sea level rise, land use change and hydrological alterations reduces the capacity of future C sequestration	Abbott *et al.*, 2019(ref. 76)
4	Salinity fluctuations	Affects microbial decomposition and carbon stability	Suonan *et al.*, 2024(ref. 56)
5	Primary productivity	Increased photosynthesis enhances sequestration potential	Geraldi *et al.*, 2019(ref. 108)
6	Biogeochemical factors	Dry bulk density, water, mud content regulates carbon stocks	Kim *et al.*, 2022(ref. 79)
		Effect of landscape movement of N input on C cycle; eutrophication reduces seagrass contribution to coastal food webs in Hainan Island, South China Sea; nutrient enrichment affects seagrass bed	Cui *et al.*, 2021(ref. 80); Li *et al.*, 2024(ref. 81); Mishra *et al.*, 2025(ref. 109); Rangesh *et al.*, 2026(ref. 120);
		Fluvial impacts – age of current vegetation communities	Kelleway *et al.*, 2017(ref. 72)
7	Climate change	Temperature rise reduces sequestration; extreme temperature fluctuations impact metabolic rates in South Florida	Fujita *et al.* (2023)(ref. 84)
		Climate oscillations drive reduced seagrass cover	Krause *et al.*, 2025(ref. 110)
8	Ocean acidification	Alters carbonate chemistry and reduces storage potential	Russell *et al.* (2024)(ref. 85)
9	Anthropogenic activities	Industrialisation leads to carbon loss; heavy metals	Sejati *et al.*, 2020(ref. 86); Gopi *et al.*, 2020(ref. 111); Thangaradjou *et al.*, 2014(ref. 112); Asha *et al.*, 2020(ref. 113) ; Thangaradjou & Kannan, 2014(ref. 114); Nair *et al.*, 1983(ref. 115); Vedharaja *et al.*, 2023(ref. 116)
10	Integrated multi trophic aquaculture	Reverse blue carbon emission and enhance C sequestration	Ahmed *et al.*, 2017(ref. 87)
11	Microbial activity	Decomposition rates influence carbon sequestration	Qin *et al.*, 2024(ref. 82)
12	Seagrass density	Higher density correlates with increased carbon storage	Kim *et al.*, 2022(ref. 79)
13	Human disturbances	Land reclamation and deforestation reduce blue carbon	Ahmed *et al.*, 2018(ref. 88)
14	Coastal development	Urbanisation reduces available habitat	Sejati *et al.*, 2020(ref. 86)
15	Non-environmental factors: National policies & commitments	About 7 % of the Asian countries reduction goal of CO_2 emission by 2030	Stankovic *et al.*, 2021(ref. 37)

compared. With a value of 184.24 Mg C/ha, the Andaman and Nicobar Islands in India were found to have the largest organic carbon (Corg) storage, followed by Myanmar (136.67 Mg C/ha) and Thailand (134.20 Mg C/ha). However, Indonesia had the lowest storage (97.60 Mg C/ha) despite having a large amount of seagrass[87-91]. According to data from Indian seagrass ecosystems, Above Ground Biomass (AGB) carbon ranges from 0.20 to 0.96 Mg C ha^{-1}, while Below Ground Biomass (BGB) carbon varies between 0.30 and 2.90 Mg C ha^{-1}. Soil carbon stocks are significant, reaching up to 139 Mg C ha^{-1} at depths of 1 m(ref. 92). Numerous variables, including coastal development, dredging, sedimentation, aquaculture, destructive fishing, water quality (pollution), mangrove plantations, tourism, shipping, tsunamis, and other climate change, have been linked to the loss of seagrass cover across the world. National policies need to be strengthened to support the improvement of seagrass cover and the reduction of CO_2 emissions.

Discussion

The extensive literature survey of seagrass and blue carbon with reference to the Indian context has revealed that a total of 59 studies have been reported, of which 20 studies specifically addressed the core aspects of blue carbon, including carbon sequestration, storage, and ecosystem services. When compared to the global research output, less than 16.5 % of studies have been conducted in the Indian seagrass ecosystem, which indicates a relatively low proportion of blue carbon-focused research and a significant research gap. Similar to the pattern observed in international waters, the high carbon sequestration potential of seagrass ecosystems is more evident in Indian coastal waters. However, due to the lack of standardised methods, the high cost of instrumentation and technology, limited scientific data, and fragmented monitoring, Indian seagrass data as blue carbon finds it difficult to get represented in global database inventories. Hence, there is an urgent need to evaluate the real-time status, spatial variability, and carbon dynamics of seagrass ecosystems in Indian coastal waters through systematic region-wise investigations. Further, it is necessary to develop a National Seagrass Monitoring Framework in India, which will facilitate standardised national reporting and monitoring of the Indian seagrass ecosystem for international organisations such as UNESCO's Intergovernmental Oceanographic Commission, and the IPCC, to recognise and integrate into the global blue carbon inventory.

Blue carbon sinks with varying sequestration potential and storage capacities from different ecosystems are comparable to terrestrial forests. The global assessment of blue carbon clearly shows that seagrass ecosystems are among the most significant carbon sinks. In this global context, India, with its vast coastline and seagrass ecosystems, will continue to emerge as a significant destination for carbon sinks. Even though the present record in India accounts for a smaller proportion of seagrass cover (500 km^2)[62], there is scope to recover the degraded seagrass beds to extend coverage. The seagrass beds in the Gulf of Mannar, Palk Bay, and the Andaman and Nicobar Islands exhibit high carbon storage efficiency. Fourqurean *et al*.[38], in their global seagrass ecosystem assessment and carbon stocks, excluded the Indian region due to a lack of sufficient scientific data[93,94]. Future studies should aim to address critical challenges, such as the need for a standardised, consistent methodology and the representation of measurement units such as Megagram Carbon (MgC) and Teragram Carbon (TgC) to facilitate better comparison of national data with global datasets.

In the global context, seagrass ecosystems, particularly *Posidonia oceanica* in the Mediterranean, play a crucial role in blue carbon sequestration. But a significant decline in their areal extent, cover, and shoot density has been observed over the last 50 years. Between 13 % and 50 % of seagrass extent has been lost, with shoot density thinning by nearly 50 %, reducing the region's carbon sink capacity by 11–52 %. Local disturbances and increasing global threats such as climate change and invasive species are key drivers of degradation[95]. Seagrass decline in Maryland, USA, between 2002 and 2004 was linked to eutrophication from nutrient-rich groundwater. At the lagoon's shallow edge, *Ruppia maritima* coexists with *Zostera marina*, but monitoring revealed significant losses nearshore, highlighting the impact of anthropogenic nutrient inputs on coastal seagrass ecosystems[96]. Coastal development, dredging, sedimentation, aquaculture, destructive fishing, water quality (pollution), mangrove plantations, tourism, shipping, tsunamis, and other climate change factors are some of the threats that tend to cause the loss or decline of seagrass beds in these areas worldwide[97]. Moreover, seagrass bed reductions are mostly caused by natural events, including floods, typhoons, tsunamis, and El Niño-Southern Oscillation (ENSO). Vietnam and Mainland China have reported declining seagrass beds over time, but Thailand has shown stability and growth in seagrass beds even after the 2004 Indian Ocean earthquake and tsunami, which indicates a natural recovery from the devastating disruption[98].

In the regional context, Asia's extensive coastlines and diverse marine ecosystems enhance blue carbon potential, which can help sustainably manage the ocean economy; however, ocean accounting is still in its early stages, and its application remains fragmented. Seagrass meadows in India are varied and are mostly found along the country's eastern and western shores, the Gulf of Mannar, Palk Bay, Chilika lagoon, Pulicat lake, Andaman and Nicobar Islands, and Lakshadweep[99-101]. These ecosystems are essential for maintaining marine biodiversity, stabilising sediments, boosting fisheries production, and providing habitat for threatened species like dugongs[102]. However, unchecked coastal expansion, destructive fishing methods, and rising marine pollution are all contributing to the rapid destruction of Indian seagrass meadows[103].

In view of blue carbon, the average sediment organic carbon in Indian seagrass meadows is up to 129 MgC ha^{-1} in the top 1 m of soil, which is comparable to parts of Australia. The ANI shows high sequestration potential (184.24 MgC ha^{-1}), acting as an efficient blue carbon sink. This reveals the geomorphological stability, intermediate hydrodynamic disturbance, and dense seagrass cover that enhance carbon burial efficiency.

Scientific reports reveal that seagrass cover is decreasing in areas such as the Gulf of Mannar and Palk Bay due to anthropogenic pressures, including coastal development, dredging, trawl fishing, nutrient enrichment, climate change, sea level rise and ocean acidification[117-121], highlighting the urgent need for national conservation action plans. In future, the survival of seagrass ecosystems in India will be dependent on proactive conservation measures like i) habitat restoration, ii) neighbourhood-based protection campaigns, and iii) policy-driven projects[104]. Their resilience may be significantly increased by incorporating seagrass habitats into India's blue carbon policies, strengthening marine protected areas, and finally implementing sustainable coastal management. Their long-term viability will also depend on further studies of the dynamics of seagrass ecosystems and their role in carbon sequestration, as well as on restoration techniques adapted to regional circumstances.

Conclusion

This review highlights the crucial role of seagrass ecosystems in global blue carbon sequestration, with significant contributions from regions including Southeast Asia, Australia, the Mediterranean, and West Africa. Large-scale degradation from local and global stressors continues to threaten seagrass meadows worldwide. The analysis highlights that regional variability in carbon stocks, species-specific differences and methodological inconsistencies remain major challenges in achieving accurate global estimates. From an Indian perspective, the seagrass carbon sequestration potential remains under represented in national climate frameworks. Key ecosystems such as the Gulf of Mannar, Palk Bay, Chilika Lake and the Andaman and Nicobar Islands exhibit promising carbon storage capacities but face the disadvantages of limited long-term monitoring, sparse field data and inadequate integration into climate policy. Environmental drivers, including hydrodynamics, nutrient fluxes, and anthropogenic pressures significantly influence seagrass biomass and sedimentary carbon storage. By addressing these variables through standardised methodologies and high-resolution spatial mapping for carbon budgeting, India can advance climate resilience and fulfil its commitments under the Paris Agreement for integrated blue carbon strategies. This comprises strengthening ocean carbon accounting systems, promoting stakeholder engagement, mainstreaming blue carbon into coastal policy and expanding research to fill existing knowledge gaps. The protection and sustainable management of India's seagrass ecosystems are vital not only for carbon mitigation but also for protecting marine biodiversity and supporting coastal livelihoods.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at https://nopr.niscpr.res.in/jinfo/ijms/IJMS_54(10)493-508_SupplData.pdf

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Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Statement

This study did not involve human participants, vertebrate animals or any procedures requiring ethical committee approval.

Author Contributions

KR: Writing – original draft, visualisation, methodology, investigation, formal analysis, data curation, and conceptualisation. RSPR: Writing – review & editing, supervision, methodology, investigation, and data curation. MD: Methodology and investigation. MA: Writing – review & editing, supervision, methodology, investigation, data curation, and conceptualisation. USP: Writing –

review & editing, supervision, project administration, methodology, investigation, data curation, and conceptualisation.

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