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Carbon Stocks, Sequestration Rates and Climate-Mitigation Potential of Indian Wetlands: An Overview

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Keywords

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Carbon stock;
Soil organic carbon;
Tree biomass carbon;
Wetland ecosystem

Abstract

Wetlands are dynamic land–water interface ecosystems that support high biodiversity and provide important regulating services, including carbon storage and climate-change mitigation. Wetlands contain substantial carbon in vegetation, soils, sediments and aquatic pools. However, carbon stock, carbon sequestration and net greenhouse-gas mitigation represent distinct processes and should not be interpreted interchangeably. Reported ecosystem carbon stocks vary substantially among wetland types, ranging from approximately 4.06 to 335.33 Mg C ha^{-1} in the studies compiled. Soil and sediment organic carbon generally constitute the dominant long-term carbon reservoirs, while vegetation contributes substantially in mangrove and other vegetated wetlands. Within these ecosystems, soil and plant biomass serve as the major reservoirs for carbon sequestration, while in water bodies the carbon concentration ranges from 3.46 to 17.77 mg L^{-1}. Across soil profiles, the surface layer (0–15 cm depth) consistently exhibits the highest carbon sequestration capacity. Despite the well-documented significance of Indian wetlands in supporting ecosystem services and mitigating climate change, critical knowledge gaps persist, particularly in long-term monitoring frameworks, standardized measurement methodologies, and systematic assessment of carbon flux potential. Addressing these gaps is essential for strengthening national carbon accounting and for informing evidence-based conservation and climate adaptation policy formulation.

1. Introduction

According to the Ramsar Convention, wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres (Grobicki et al., 2016). It is either permanent or seasonal, natural or man-made, and this has a significant impact on the vegetation and wildlife living there (Keddy, 2010; Tiner, 2016). Natural wetlands, including lagoons, backwaters, estuaries, mangrove swamps, natural lakes, and coral reefs, while man-made wetlands are built for a purpose, such as storing water for irrigation, for fish cultivation, for recreation, and include as reservoirs, aquaculture ponds, salt pans, dams,

barrages, lakes, etc. (Fig. 1) (Garg and Patel, 2007). Wetlands stand out as one of the most thriving ecosystems within our natural surroundings. A peatland is a type of terrestrial wetland where saturated, waterlogged conditions prevent the full decomposition of plant material, leading to the accumulation of partially decomposed organic matter called peat over centuries. Peatlands are usually found in cool or wet climates, including the high latitudes of the northern hemisphere, accompanied by freshwater (Craft, 2022). Under the Ramsar Convention, wetlands of international importance are designated as Ramsar Sites. These sites are recognized for their ecological, botanical, zoological, limnological, or hydrological significance, including their importance for migratory waterbirds, support for threatened or vulnerable species, their ecological uniqueness, and their cultural or scientific value (Frazier, 1999; Stroud and Davidson, 2021).

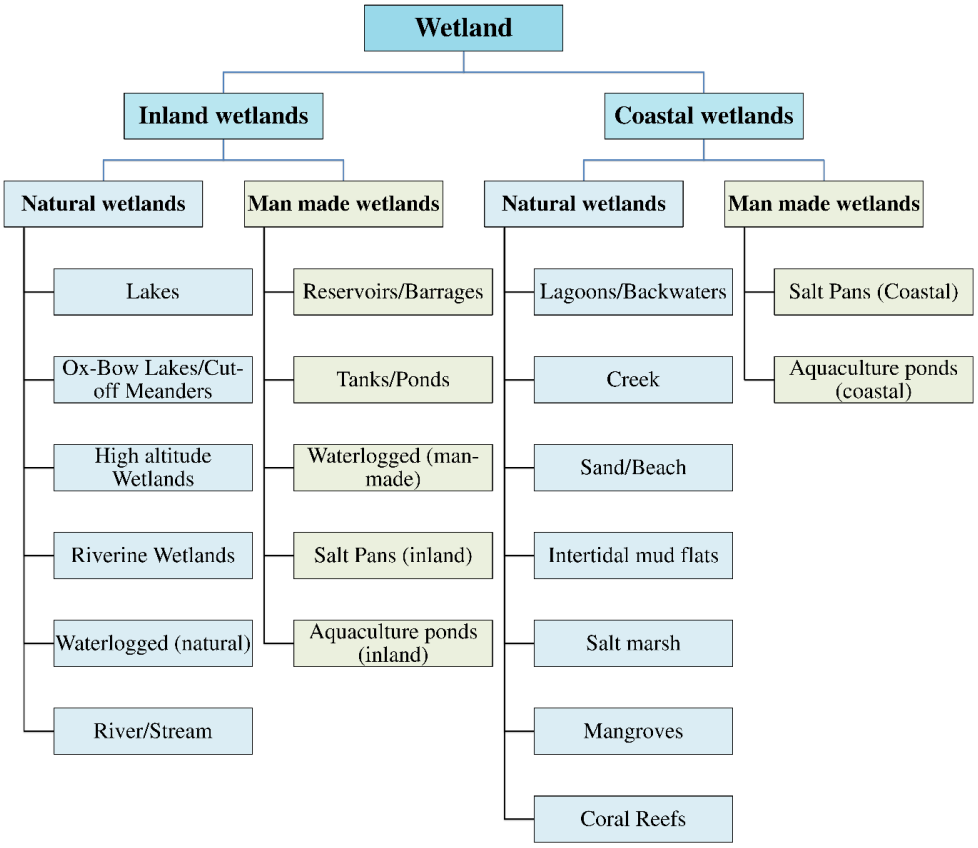


Fig. 1. Classification of wetlands according to Garg and Patel (2007)

Wetlands are a valuable natural resource and are essential for maintaining the planet's biodiversity, making up 5 to 8% of the earth's land surface and occurring in freshwater, saltwater, or brackish environments (Cherry, 2011; Juffe-Bignoli et al., 2018). They are important for maintaining environmental processes and provide a variety of ecosystem services necessary for human survival. In India, wetlands support one-fifth of India's biodiversity and account for 152,600 km^2 (4.63%) of the country's total land area (Bassi et al., 2014). In 2022, the Wetlands Change Atlas of India documented 231,195 wetlands, constituting 4.86% of the country's total land area. These areas lie in the transitional zone between land and water, straddling neither pure land nor pure water. The scientific study focused on these wetlands is known as paludology. As of 2026, India has 103 designated Ramsar sites (wetland of international importance), covering a total

surface area of 15,61,308 hectares. Wetlands consist of a diverse range of areas known by various names such as marshes, bogs, swamps, fens, pocosins, and more. The Hindu Kush-Himalayan region's wetlands are made up of lakes, marshes, peat bogs, wet grasslands, streams, and rivers (Wetlands of Uttarakhand, 2012). The wetlands ecosystem composition and structure vary widely, depending on abiotic factors as well as distinctive biotic species and processes, and are characterized by an intricate web of plant diversity and carbon dynamics, which stands as a testament to the intricate interplay between flora, fauna, and environmental processes (Euliss et al., 2004; Kingsford et al., 2016). Wetlands enhance nutrient cycling, provide food and fiber, reduce flooding, and help regulate the composition of the atmosphere through carbon dynamics (Kingsford et al., 2016); assessing their terrestrial and aquatic plant diversity therefore also sheds light on their role in carbon sequestration and climate mitigation.

Carbon dioxide (CO_2) alone accounts for 60% of greenhouse gases that contribute to global warming, which has increased the planet's average temperature by 0.72°C (1.4°F) during the previous century (NCAR, 2014). To reduce global warming and prevent the harmful effects of climate change, carbon sequestration is the process of capturing and permanently storing atmospheric carbon dioxide (Dhanwantri et al., 2014). Wetlands are crucial to the global carbon cycle and serve as substantial carbon sinks because they are highly productive ecosystems that store a lot of organic matter in the soil (Chmura et al., 2003; Mitra et al., 2005). The hydro-geochemical properties of the ecosystem, which in turn shape wetland vegetation communities, have a significant impact on the amount of carbon wetland vegetation communities accumulate and emit each year (Bernal and Mitsch, 2012). Increasing carbon storage in tree biomass and soil organic matter, and carbon sequestration operations can help mitigate global climate change (Khurana, 2012). Carbon stock, carbon concentration, carbon sequestration, and net greenhouse-gas balance describe different components of wetland carbon dynamics. Carbon stock represents the quantity of carbon stored within a defined ecosystem pool such as wetland vegetation, litter, soil, sediment, or water, and is commonly expressed as Mg C ha^{-1}. In contrast, carbon sequestration is a temporal process and should be expressed as an annual carbon storage rate in different carbon pools. Carbon sequestration represents the net accumulation of carbon through time and therefore requires an explicit temporal dimension and is normally expressed as Mg C ha^{-1} yr^{-1}. An ecosystem, including wetlands, may contain a large legacy carbon stock while exhibiting little contemporary carbon accumulation, or it may even function as a net greenhouse-gas source under altered hydrological or biogeochemical conditions; it may be near equilibrium or may become a net source following vegetation type, drainage, degradation, or hydrological alteration. Consequently, evaluating the climate-mitigation role of wetlands requires information on both existing carbon stocks and ongoing carbon gains and losses.

Natural ecosystems such as wetlands are among the most important, cost-effective, and efficient options for sequestering atmospheric CO_2 (Adhikari et al., 2009; Lal, 2008; Lane et al., 2016; Mitra et al., 2005; Nahlik and Fennessy, 2016; Villa and Bernal, 2018; Yu et al., 2012). Wetlands are among the most carbon-dense ecosystems on this blue planet and play a critical role in the global carbon cycle. They function as both carbon sinks and sources depending on hydrological conditions, vegetation dynamics, and biogeochemical processes. Wetlands are among the most productive ecosystems and have the highest soil carbon density relative to other ecosystems, such as forests and grass/shrublands (Kayranli et al., 2010; Zeng et al., 2014; Villa and Bernal, 2018). The IPCC argues that effective carbon sequestration requires enhancing natural

ecosystems. The arguments are that either human disturbance (Lal, 2005, 2008; Howe et al., 2009; Davidson, 2014; Zhang et al., 2015; Nahlik and Fennessy, 2016) or global climate change (Post et al., 2004; Erwin, 2009; Kayranli et al., 2010; DeLaune and White, 2012; Moomaw et al., 2018) has decreased the capacity of these ecosystems to sequester carbon. The organic matter accretion rates are in the order of millimetres to 1 cm yr^{-1} for both constructed and natural wetlands (Pant et al., 2003). Soil carbon in wetlands is recognized as an important component of global carbon budgets and hence has received significant research interest in understanding and enhancing the mechanisms of sequestration (Rapalee et al., 2001; McCarty and Ritchie, 2002; Richey et al., 2002; Thom et al., 2002). Globally, the potential of wetlands in sequestering carbon is still substantial (Amthor and Huston, 1998; Brix et al., 2001; Whiting and Chanton, 2001). Soil Organic Carbon (SOC) is the largest carbon pool in most wetland soils and consists of partially decomposed plant and microbial residues stabilized within soil aggregates. Due to anaerobic conditions and slow decomposition rates, wetlands accumulate large amounts of SOC, making them long-term carbon sinks. Peatlands and marshes are especially significant, storing nearly one-third of global soil carbon despite occupying a relatively small land area (Lal, 2005; Mitsch and Gosselink, 2015). Soil Inorganic Carbon (SIC) primarily includes carbonates such as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). While SIC is more dominant in arid and semi-arid regions, it also occurs in certain wetlands influenced by groundwater chemistry and carbonate-rich parent materials. SIC contributes to long-term carbon storage through pedogenic carbonate formation and geochemical precipitation processes. In some wetland systems, interactions between SOC mineralization and carbonate dynamics influence CO_2 fluxes and soil buffering capacity (Eswaran et al., 2000).

Dissolved Organic Carbon represents the fraction of organic carbon that is soluble in water and passes through a 0.45 μm filter. In wetlands, DOC originates from plant litter decomposition, root exudation, microbial activity, and leaching of organic matter. It plays a crucial role in nutrient transport, microbial metabolism, and downstream aquatic carbon export. Wetlands often act as major sources of DOC to rivers and lakes, influencing water chemistry and carbon fluxes at landscape scales (Battin et al., 2009). Carbon sequestration, generally, denotes the process involved in the capture and long-term storage of atmospheric carbon (CO_2) in natural or human-engineered sinks. Wetland carbon sequestration refers to the capture of atmospheric CO_2 and its long-term storage in various components of wetland ecosystems, with minimal chances of being released back into the atmosphere (Were et al., 2019). In quantitative terms, carbon sequestration is an expression representing a change in carbon stocks, either in or between wetland ecosystems. The definite amount of carbon a wetland can sequester on a given temporal and spatial scale, termed carbon sequestration potential, denotes both the maximum rate of carbon storage (for example, the rate of growth of plants) and the maximum amount of carbon that can be stored (for example, in plants or soil) (Zhu et al., 2010). How long the stored carbon stays in the wetlands is still a debatable question, though several studies indicate that undisturbed wetlands can store carbon for several hundreds of years to millennia (Mitra et al., 2005; Kurnianto et al., 2015; Ezcurra et al., 2016). The present review was undertaken to assess carbon stocks and sequestration across various wetland ecosystems of India, with a focus on different carbon pools. This assessment aims to evaluate the role of wetlands in carbon sequestration and their potential contribution to climate change mitigation.



Fig. 2. Overview of wetland ecosystem (Asan Conservation Reserve- Ramsar Wetland (man-made), Dehradun, Uttarakhand)

2. Material and Methods

This study used a structured literature-review and evidence-synthesis approach to synthesize existing scientific evidence on wetlands and their potential for carbon sequestration and climate-change mitigation, with a focus on India. To thoroughly assess the carbon storage potential of Indian wetlands, a structured and transparent literature compilation process was followed. A comprehensive search of peer-reviewed literature was carried out using major academic databases, including Google Scholar, Web of Science, ResearchGate, and Academia.edu. The search strategy combined keywords such as "wetland," "carbon stock," "carbon sequestration," "soil organic carbon," "sediment carbon," "blue carbon," and "climate change mitigation," together with the geographic qualifier "India." Boolean operators (AND, OR) were used to refine the search and ensure the retrieval of relevant studies. While no strict temporal restriction was applied, priority was given to studies published after 2000 to maintain consistency with contemporary carbon estimation methodologies and improved analytical accuracy.

The retrieved records underwent a multi-stage screening process. First, titles and abstracts were reviewed to remove irrelevant or duplicate publications. Next, full-text articles were assessed according to predefined inclusion criteria. Studies were included if they (i) were conducted within the geographical boundaries of India, (ii) reported quantitative estimates of carbon stocks and/or sequestration rates, and (iii) measured at least one major carbon pool, such as aboveground biomass carbon, belowground biomass carbon, soil organic carbon, or sediment carbon. Studies without empirical carbon measurements, purely descriptive ecological reports, or opinion-based articles were excluded from further analysis. From the selected studies, relevant information was systematically extracted and organised into a structured database. Extracted variables included geographic location (state or region), wetland type, carbon pools measured, carbon stock values, carbon sequestration rates, soil or sediment sampling depth, and year of study. The compiled dataset was analysed using descriptive methods to assess variability in carbon stocks across

wetland types and regions of India. Although variability in methodological approaches among studies represents a limitation, the systematic compilation and standardized comparison of data provide a robust assessment of the role of Indian wetlands in national climate change mitigation strategies, in alignment with global recognition of wetlands as critical natural climate solutions (Moomaw et al., 2018).

3. Results and Discussion

3.1 Wetlands for carbon stock and climate change mitigation: Wetlands are highly effective natural carbon sinks that play a crucial role in mitigating climate change (Adhikari et al., 2009; Zhang et al., 2025). Their ability to accumulate vast amounts of carbon in soils and vegetation often outweighs their methane emissions when considered over long timescales, positioning them as net sinks in the global greenhouse gas budget. Wetlands include diverse ecosystems such as peatlands, mangroves, salt marshes, tidal marshes, and seagrass beds, all of which have unique hydrological and biogeochemical properties that enable them to store carbon for millennia (Chmura et al., 2003; Choudhary et al., 2024; Vasumathi et al., 2025). Despite covering only 5–8% of Earth's land surface, wetlands regulate ~68% of terrestrial soil carbon reserves (Kumar et al., 2023) and hold approximately 20 to 30% of all terrestrial carbon, making them disproportionately important in the global carbon budget (Lal, 2008). Their ability to absorb and store carbon dioxide (CO_2) and other greenhouse gases stems largely from the waterlogged, anoxic conditions in wetland soils, which slow decomposition and promote long-term organic matter accumulation (Schuster et al., 2024; Song et al., 2024). The capacity of wetlands to sequester carbon is primarily a result of their anaerobic soil conditions. In water-saturated environments, oxygen diffusion is limited, and microbial decomposition of organic matter proceeds very slowly (Tolunay et al., 2024). As a result, plant material such as leaves, stems, and roots accumulates in the soil, forming peat and other organic-rich deposits. This process of slow decomposition and organic matter burial allows carbon to be stored for centuries to millennia. Peatlands, in particular, are the most efficient carbon sinks on Earth; although they cover only about 3% of the terrestrial surface, they store nearly one-third of global soil carbon (Weissert and Disney, 2013). Coastal wetlands such as mangroves, salt marshes, and seagrass beds also demonstrate exceptionally high rates of carbon burial and are collectively referred to as "blue carbon" ecosystems (Singh and Shanmugam, 2020; Rani et al., 2023). Apart from carbon sequestration, wetland ecosystems also provide provisioning, regulating, cultural, and supporting ecosystem services (Salimi et al., 2021).

The climatic role of wetlands therefore reflects a trade-off between long-term carbon accumulation and contemporary greenhouse-gas exchange. Although wetlands are strong carbon sinks, they also emit methane (CH_4), a greenhouse gas with a global warming potential 28–34 times greater than CO_2 over a 100-year time horizon (IPCC, 2013; Schuster et al., 2024). Methane (CH_4) is the second most important greenhouse gas after carbon dioxide. Methane production is favoured by anoxic conditions that develop under prolonged soil saturation, whereas CH_4 oxidation may occur in oxygenated soil zones. Methane efflux, defined as the release of CH_4 from terrestrial and aquatic ecosystems such as wetlands, forests, and inland water bodies into the atmosphere, plays a crucial role in regulating atmospheric greenhouse gas concentrations. Consequently, water-table position, hydroperiod, vegetation, temperature, organic-substrate availability and salinity strongly influence the magnitude of methane emissions. Hydrological fluctuations have been identified as an important source of uncertainty in wetland methane

dynamics (Cui et al., 2024). Wetlands are recognised as the largest natural source of methane emissions, while forest soils can act as either sources or sinks depending on environmental conditions (Le Mer and Roger, 2001). Methane is generated in anaerobic soils through microbial methanogenesis and released to the atmosphere via diffusion, ebullition, or transport through plant tissues (Rajendran et al., 2024). This dual role creates a complex greenhouse gas balance. Soil organic matter serves as a primary substrate for methanogenic microorganisms, thereby influencing methane production rates. Over centennial timescales, the climate benefit of CO_2 sequestration generally outweighs the warming impact of CH_4 emissions, rendering most wetlands net greenhouse gas sinks (Whiting and Chanton, 2001). However, over shorter time horizons, some wetland types, particularly peatlands and inland freshwater marshes, may function as net greenhouse gas sources, as methane emissions dominate in the short term (Sun et al., 2018). Baiswar et al. (2026) reported that the freshwater wetlands of the Doon Valley of Uttarakhand function as measurable greenhouse-gas sources despite their ecological importance and potential carbon-storage functions. In contrast, coastal wetlands such as mangroves and salt marshes produce relatively little methane because high salinity favours sulfate-reducing bacteria over methanogens, enhancing their role as net climate coolers.

Human intervention can significantly alter the greenhouse gas balance of wetlands (Sarkar et al., 2023). Drainage of wetlands for agriculture or development exposes previously anoxic soils to oxygen, accelerating decomposition and releasing large amounts of stored carbon. The drainage of peatlands, for example, has been identified as one of the largest sources of land use-related CO_2 emissions worldwide. Conversely, the protection and restoration of wetlands are effective strategies for improving climate protection (Keddy, 2010; Kingsford et al., 2016). Rewetting drained peatlands, replanting mangroves, and restoring tidal streams can restore CO_2 uptake and slow carbon losses. The restored wetlands show that CO_2 uptake rates can exceed those of natural wetlands within a few years, emphasizing the rapid climate benefits of restoration. However, restoration can also increase methane emissions, particularly in freshwater systems, emphasizing the importance of careful hydrological and vegetation management. The role of wetlands in mitigating climate change is further complicated by the effects of global warming. Rising temperatures may accelerate decomposition and methane production, while rising sea levels and changing precipitation regimes threaten the integrity of coastal and inland wetlands (Erwin, 2009). Despite these risks, wetlands remain one of the most effective natural solutions to climate change. Due to their long-lived carbon stores, they are crucial in avoiding the release of huge “carbon debts” that would otherwise exacerbate global warming. The inclusion of wetlands in national climate policies, the promotion of blue carbon initiatives, and other governmental and non-governmental measures and projects can further maximize their mitigation potential. Protecting intact wetlands, restoring degraded wetlands, and integrating them into climate policy frameworks are therefore urgent priorities to preserve their role as natural carbon sinks and improve global resilience to climate change.

3.2 Various carbon pools of wetland ecosystems: Wetland ecosystems, with their multiple carbon pools that regulate carbon storage and exchange, are critical components of the global carbon cycle. These ecosystems act as major carbon sinks due to their anaerobic conditions, which slow decomposition (Chmura et al., 2003; Kayranli et al., 2010; Bhomia et al., 2016). Collectively, the vegetation, soils, water, and gaseous fluxes of wetlands form an interconnected system that influences both global carbon cycling and climate regulation (Salimi et al., 2021). The wetland

ecosystem comprises various carbon pools (Fig. 3), including living biomass (plants and animals), dead organic matter (including litter and detritus), soil carbon (soil organic matter in hydric soils), and dissolved organic matter in wetland waters (Vinod et al., 2019; Li et al., 2024) that can be further classified under various subgroups. Broadly, the wetland carbon pools can also be classified as terrestrial (including soil, vegetation, and other plant-based residues) and aquatic carbon pools (Ray et al., 2011). Vegetation represents an important carbon pool, as living plants capture atmospheric CO_2 through photosynthesis and store it as above- and below-ground biomass. Aboveground biomass includes leaves, stems, and other visible plant parts, such as trees in forested wetlands and grasses in marshes, while belowground biomass consists of roots and rhizomes that also store significant amounts of carbon (Bhomia et al., 2016). In particular, the roots of macrophytes contribute oxygen to the soil, suppressing methane production in the rhizosphere. Additionally, standing dead organic matter provides a temporary carbon reservoir before transitioning into litter or soil organic matter. Soil carbon pools are the largest and most significant reservoirs in wetlands, with wetland soils holding a disproportionate share of global soil carbon despite covering a relatively small land area (Mitra et al., 2005; Kaladharan et al., 2022). The dominant pool is soil organic carbon (SOC), which accumulates as dead plant material decomposes slowly under waterlogged, oxygen-limited conditions. In peatlands, this process results in the buildup of organic matter over centuries or millennia. Wetlands may also store soil inorganic carbon in the form of carbonates, particularly in arid or semi-arid regions influenced by mineral-rich groundwater. Despite being more stable than organic carbon in soil, inorganic carbon can be mobilized in acidic environments, including those brought on by acid rain.

The water column of wetlands contains both dissolved and particulate forms of carbon that link terrestrial and aquatic processes (Nag et al., 2025). Dissolved organic carbon, derived from decomposing organic matter and root exudates, can either be transported downstream or utilized by microorganisms. Dissolved inorganic carbon, including CO_2, bicarbonates, and carbonates, is influenced by atmospheric exchange and chemical processes such as carbonate dissolution and precipitation (Nag et al., 2025). These dissolved forms of carbon are also accessible to aquatic plants and algae, supporting primary productivity within wetland waters. Wetlands also exchange carbon directly with the atmosphere through gaseous fluxes (Salimi et al., 2021). They take up CO_2 via photosynthesis and release it through respiration, with the balance between uptake and release determining their role as either a net sink or source. Methane, produced through anaerobic microbial activity (methanogenesis), represents a particularly important gaseous pool because of its high global warming potential (Salimi et al., 2021; Li et al., 2024). However, methane emissions are partly mitigated by methanotrophic bacteria that consume CH_4 before it escapes to the atmosphere.The overall carbon balance of wetlands depends on factors such as water level, temperature, vegetation type, and hydrological conditions, but over long timescales, wetlands generally function as significant carbon sinks despite methane emissions. An important conceptual distinction is also required between carbon pools and carbon fluxes. Vegetation biomass, litter, dead organic matter, soils, sediments and dissolved or particulate carbon in water constitute carbon pools or reservoirs at a particular time. In contrast, photosynthetic CO_2 uptake, ecosystem respiration, CH_4 emission, sediment burial and lateral export of dissolved or particulate carbon represent fluxes that transfer carbon among pools or between the wetland and the atmosphere or adjacent terrestrial ecosystems.

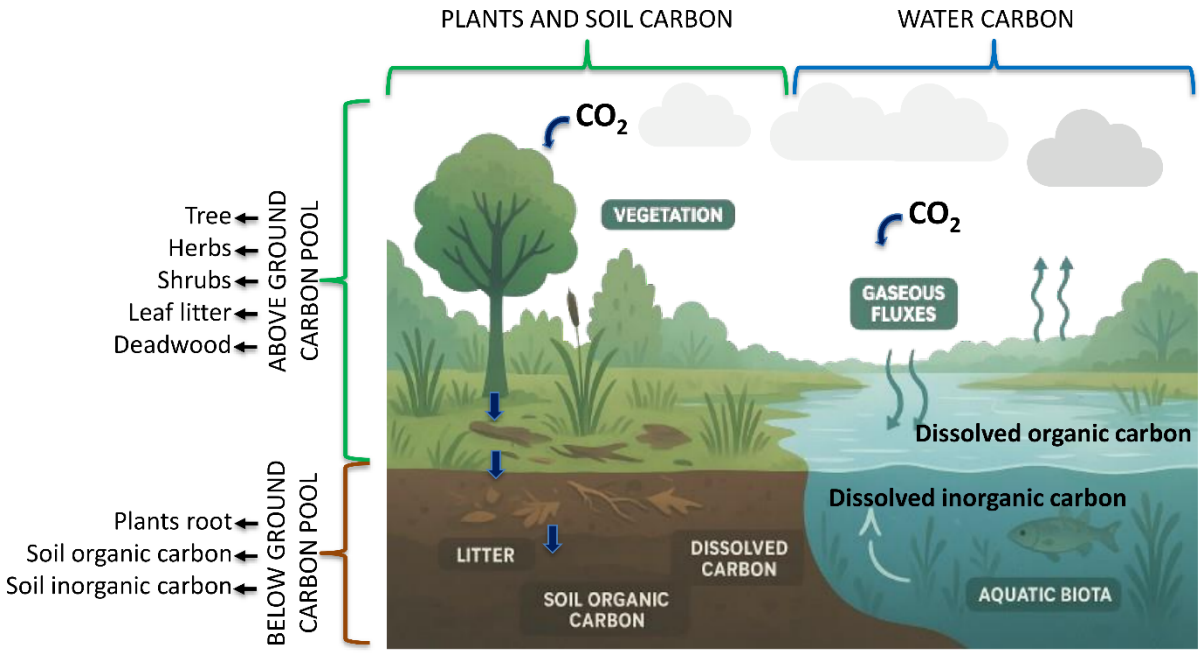


Fig. 3. Overview of various carbon pools in wetland ecosystems.

3.3 Carbon stock potential of Indian wetlands: Global warming and climate change are the most severe challenges facing human society and are directly related to the survival and development of humankind throughout the world (IPCC, 2013). In India, the impact of climate change is more significant and severe than the global average due to its geographical vulnerability and high population density, which lead to increased heatwaves, extreme flooding, droughts, cyclones, and health and economic consequences that disproportionately affect children, the elderly, and labourers (Srinivasan, 2012; Pande et al., 2023).

The higher impact of climate change in India can be reduced through effective management, minimizing greenhouse gas emissions, and enhancing the sequestration and long-term storage of gases that cause global warming and climate change. Since carbon dioxide (CO_2) plays a significant role in increasing global temperatures and driving climate change, it is essential to reduce its concentration in the atmosphere. According to the Wetlands of India Portal, the country has a total of 101 Ramsar wetland sites, which are wetlands recognized for their international importance, and the total number of wetlands is 1,311, while the National Wetland Inventory and Assessment project mapping in the year 2017 mapped 2,31,195 wetlands all over India. Therefore, we assessed the role of Indian wetlands in carbon sequestration and climate change mitigation, as it is an important ecosystem service that wetlands provide. The biogeochemistry underlying the process of carbon sequestration in wetlands is relatively well understood. However, anthropogenic activities, especially conversion to other land uses, are affecting their capacity to sequester carbon. This issue has necessitated finding options to enhance the ability of wetlands to sequester carbon and enable them to remain relevant in global carbon balance and climate change mitigation. Various studies have documented several measures that seek to enhance carbon sequestration of wetlands and therefore enable these ecosystems to remain vital in the global carbon balance (Adhikari et al., 2009; Kayranli et al., 2010; Were et al., 2019).

The carbon sequestration and stock in various carbon pools of different wetland ecosystems of India are listed in Table 1. High ecosystem carbon stocks may represent centuries of accumulated organic matter, whereas comparatively low stocks may characterize younger or more frequently disturbed systems that nevertheless exhibit rapid contemporary carbon accumulation. Consequently, the stock values compiled in this review are interpreted primarily as indicators of existing carbon reservoirs rather than direct measures of annual sequestration. The analysis of carbon stocks across diverse Indian wetland ecosystems highlights significant heterogeneity in carbon storage, driven primarily by ecosystem type, vegetation density, soil composition, and hydrological factors. Among the various carbon pools, wetland soils and sediments are considered among the world's largest carbon sinks. Mangrove ecosystems consistently showed high carbon storage potential compared to seagrass meadows and floodplain wetlands, such as Kochi mangroves, with a total carbon stock of 335.33 ± 184.47 t C ha^{-1}, reflecting the crucial role of mangrove forests as carbon sinks, primarily due to dense vegetation and high biomass productivity, corroborating earlier findings (Rani et al., 2023). Soil organic carbon stocks varied with depth and seasonality, particularly in coastal wetlands. Nag et al. (2025) reported that the soil carbon stock at different depths (0–15 and 15–30 cm) of the wetlands varied widely from 1.3 to 7%. The total carbon was accumulated in the top 30 cm, ranging from 12.65 to 76.95 Mg C ha^{-1}, while the corresponding upland sites contained 8.8–33.62 Mg C ha^{-1}. Taran et al. (2023) reported that the average soil organic carbon stock was estimated at 230 ± 94 Mg C ha^{-1} in an inland freshwater wetland in Northeast India. Banerjee et al. (2022) reported that soil organic carbon in the Bhitarkanika wetlands, Odisha, ranged from 0.24 ± 0.14% to 3.57 ± 0.80% at soil depths of 0–10, 10–20, 20–30, 30–40, and 40–50 cm. Arathy et al. (2022) observed that sediment (soil) carbon stocks in Vembanad Lake, Kerala, varied seasonally. In the post-monsoon period, stocks ranged from 6.00–39.00 Mg C ha^{-1} (0–10 cm), 6.43–83.52 Mg C ha^{-1} (0–20 cm), and 17.10–139.96 Mg C ha^{-1} (0–30 cm). During the pre-monsoon period, values ranged from 2.00–35.00 Mg C ha^{-1}, 9.88–55.38 Mg C ha^{-1}, and 17.10–84.58 Mg C ha^{-1} at the same depths. In contrast, the soil carbon stock at 0–30 cm depth was much lower in Chilika Lake (Odisha) and Pulicat Lake (Andhra Pradesh), with values of 2.018 ± 0.673 Mg C ha^{-1} and 0.998 ± 0.418 Mg C ha^{-1}, respectively (Kaladharan et al., 2021). Similarly, Sarkar et al. (2023) reported a soil carbon stock of 76.95 t C ha^{-1} in the top 30 cm of the Chatla wetland, Assam.

Vegetation also constitutes a significant component of wetland ecosystems and serves as an important carbon pool. Several studies have quantified carbon stocks in vegetation, including above- and below-ground biomass. For example, Sarkar and Das (2020) estimated the total carbon stock of tropical floodplain wetlands in Assam at 21.75 Mg C ha^{-1}, comprising vegetation (3.18 Mg C ha^{-1}; 14.62%), saturated soil (8.53 Mg C ha^{-1}; 39.22%), and unsaturated soil (10.04 Mg C ha^{-1}; 46.16%), with an annual carbon sequestration potential of 6.36 Mg C ha^{-1} yr^{-1}. Vinod et al. (2019) reported above-ground carbon at 94.63 ± 48.90 t C ha^{-1}, root carbon at 41.53 ± 20.24 t C ha^{-1}, and sediment carbon at 17.48 ± 7.30 t C ha^{-1}. Singh and Shanmugam (2020) observed tree carbon stocks ranging between 16.31 and 32.61 t ha^{-1} in the Pichavaram mangrove forest, Tamil Nadu. Rani et al. (2023) documented a total ecosystem carbon stock of 335.33 ± 184.47 t C ha^{-1}, comprising 171.68 ± 104.42 t C ha^{-1} aboveground biomass, 83.30 ± 41.98 t C ha^{-1} belowground biomass, 7.12 ± 2.81 t C ha^{-1} litterfall, and 73.22 ± 39.40 t C ha^{-1} soil carbon. The historical soil carbon sequestration rate was estimated at 2.95 t C ha^{-1} yr^{-1}. At Sambhar Lake, the SOC stock was 143 t C ha^{-1} in October and 119 t C ha^{-1} in April, while at Keoladeo National Park wetland, it was 251 t C ha^{-1} in October and 164 t C ha^{-1} in April (Kumar and Sharma, 2025). Sambhar Lake retains

between 32,929.1 and 27,298.7 tonnes of carbon despite considerable seasonal variability. In contrast, during the post-monsoon (October) and pre-monsoon (April) periods, Keoladeo National Park wetland soil carbon storage capacity was approximately 7,037.8 and 4,594 tonnes, respectively. The Mahanadi Mangrove Wetland recorded mean carbon stocks of about 147.0 Mg C ha^{-1}, while mangrove forests of the Andaman Islands showed much higher vegetation carbon (290.26 Mg C ha^{-1}) (Sahu et al. 2016); however, lower carbon stocks were reported from the Gulf of Kutch mangroves (54.10 Mg C ha^{-1} vegetation carbon) (Sigamani et al. 2023). Soil organic carbon showed a clear influence on methane efflux as CH_4 uptake, as Lee et al. (2023) highlight that SOC exerts a dual control on methane dynamics, acting as a driver of both CH_4 consumption and production depending on soil moisture and aeration conditions. Although water-column and aquatic-macrophyte carbon pools are less quantified, available Indian studies mainly report carbon concentrations or standing biomass rather than rates of sequestration. Caroline et al. (2024) reported aquatic macrophyte carbon stocks of 577.38 ± 58.84 g C m^{-2} in Loktak Lake and 1442.43 ± 276.85 g C m^{-2} in Keibul Lamjao National Park, Manipur. Nag et al. (2025) found that total inorganic carbon in water ranged from 2.24 ± 0.96 to 26.74 ± 5.52 mg L^{-1} across wetlands in the Morigaon and Kamrup districts of Assam. Similarly, Singh et al. (2025) reported total carbon stocks in Phumdi wetlands ranging between 4.06 ± 1.59 and 14.94 ± 5.73 Mg C ha^{-1}.

Among the recorded carbon stocks of various wetlands (Table 1), Vembanad Lake and Sundarbans highlighted seasonal influences, with monsoonal cycles affecting organic carbon inputs and decomposition rates. The post-monsoon consistently showed higher sediment carbon stocks compared to the pre-monsoon, indicating organic matter accumulation during wet periods and reduced decomposition due to waterlogging (Arathy et al., 2022). Seagrass-dominated systems (Chilika, Pulicat, and Lakshadweep lagoons) stored relatively low carbon stocks compared to mangroves. This aligns with global patterns where seagrass meadows have modest carbon accumulation rates due to lower biomass but still contribute significantly to blue carbon storage on a per-area basis (Kaladharan et al., 2021; Murugan et al., 2024). Interestingly, inland freshwater wetlands such as the Assam floodplains and the Chatla wetland exhibited moderate carbon stocks, with substantial proportions in unsaturated and saturated soils (Sarkar and Das, 2020). These wetlands showed a considerable potential for carbon sequestration despite lower above-ground biomass, emphasizing the role of soil carbon storage in wetland ecosystems (Nag et al., 2025). Aquatic macrophyte-dominated systems (Loktak Lake and Keibul Lamjao National Park) also displayed significant carbon content, supporting their role in carbon storage at a regional scale (Caroline et al., 2024). The observed variation in carbon stocks demonstrates that Indian wetlands differ substantially in their capacity to retain carbon. However, these differences do not necessarily indicate corresponding differences in current sequestration rates. High stocks may reflect centuries of accumulation, whereas low stocks may occur in young but rapidly accumulating wetlands. The observed variations across different locations reflect the combined effects of anthropogenic pressure, local hydrology, vegetation cover, and sediment properties. Conservation and restoration strategies must prioritize mangrove protection while also enhancing the role of freshwater and seagrass wetlands in carbon sequestration, especially given their vulnerability to land-use change and climate variability.

3.4 Carbon-sequestration rates in Indian wetlands: A limited number of studies have quantified annual carbon sequestration rates in Indian wetlands (Table 2). In the Indian Sundarbans, live-biomass carbon accrual was estimated at 4.71–6.54 Mg C ha^{-1} yr^{-1} (Ray et al. 2011). However,

litterfall represented a major transfer from the live-biomass pool and reduced the estimated net live-biomass sequestration to approximately 1.69 Mg C ha^{-1} yr^{-1}, while sediment carbon sequestration was reported as approximately 0.012 Mg C ha^{-1} yr^{-1}. These findings demonstrate that gross biomass increment may substantially exceed net sequestration when ecosystem carbon losses and transfers are considered. In Kochi mangroves, the historical sediment (soil) carbon sequestration rate was estimated at 2.95 Mg C ha^{-1} yr^{-1} (Rani et al. 2023).

Table 1. Recorded carbon stock in various carbon pools of different wetlands of India.

Wetland	**Location**	**Reported Carbon Stock (t C ha^{-1})**	**Pool**	**Reference**
Sundarbans mangroves	West Bengal	Tree carbon ranged from 35.92 to 90.76 t C ha^{-1}. Soil organic carbon (%) at 0–30 cm depth- Pre-monsoon = 0.514, monsoon = 0.649, post-monsoon = 0.654	Above- and below-ground tree biomass and soil organic carbon	Ray et al. (2011)
Kerala mangroves (regional mean)	Kerala	Mean ecosystem C 139.82 t C ha^{-1} (vegetation carbon and soil carbon stock (0-60 cm depth) ranged between 58.56 to 123.28 and 52.04 to 100.80 t C ha^{-1}, respectively)	Ecosystem carbon (vegetation and soil carbon)	Harishma et al. (2020)
Vembanad Lake (*Avicennia officinalis* sediments)	Kerala	Sediment blue carbon stock in the post-monsoon ranged from 6.00–39.00 Mg ha^{-1} (0–10 cm), 6.43–83.52 Mg ha^{-1} (0–20 cm), and 17.10–139.96 Mg ha^{-1} (0–30 cm). In the pre-monsoon, it ranged from 2.00–35.00 Mg ha^{-1}, 9.88–55.38 Mg ha^{-1}, and 17.10–84.58 Mg ha^{-1} at the same depths.	Sediment (soil) carbon	Arathy et al. (2022)
Bhitarkanika mangroves (Bhitarkanika Conservation Area)	Odisha	Average soil C pools for aquaculture, planted, scrub, and dense mangroves were 61 ± 8, 92 ± 20, 177 ± 14, and 134 ± 17 Mg C ha^{-1}, respectively. Total ecosystem C stocks were 0.07 Tg in aquaculture (12 km^2), 0.25 Tg in planted/restored mangroves (24 km^2), 2.29 Tg in scrub (93 km^2), and 0.89 Tg in dense mangroves (38 km^2).	Soil and total ecosystem carbon assessed across land-use types	Bhomia et al. (2016)
Chilika Lakes	Odisha	Blue carbon stock (0–30 cm) was 2.018 ± 0.673 Mg C ha^{-1}	Seagrass sediment organic carbon to 30 cm	Kaladharan et al. (2021)
Pulicat Lakes	Andhra Pradesh	Blue carbon stock (0–30 cm) was 0.998 ± 0.418 Mg C ha^{-1}		
Pulicat Lakes	Andhra Pradesh	Species (seagrass) carbon ranged between 0.49 to 9.52 Mg ha^{-1} and soil carbon ranged between 1.29 to 11.90 Mg ha^{-1}	Seagrass soil carbon to 1 to 1.5 m	Murugan et al. (2024)
Lagoons of Lakshadweep Archipelago	Lakshadweep	The carbon stock ranged between 0.3796 Mg C ha^{-1} (at Bangaram lagoon) to 0.9795 Mg C ha^{-1} (at Thinnakara lagoon)	Soil organic carbon	Kaladharan et al. (2022)
Pichavaram mangrove forest	Tamil Nadu	Biomass carbon ranged between 16.31 to 32.61 t ha^{-1}	Tree biomass carbon	Singh and Shanmugam (2020)
Kochi mangrove forest	Kerala	Total ecosystem carbon stock was 335.33 ± 184.47 t C ha^{-1}, with 171.68 ± 104.42 t C ha^{-1} above-ground, 83.30 ± 41.98 t C ha^{-1} below-ground, 7.12 ± 2.81 t C ha^{-1} litterfall, and 73.22 ± 39.40 t C ha^{-1} soil carbon. The historical soil C sequestration rate was 2.95 t C ha^{-1} yr^{-1}.	Ecosystem carbon stock, including above- and below-ground plant biomass, leaf litter and soil organic carbon	Rani et al. (2023)
Tropical Floodplain Wetlands	Assam	Total carbon stock was 21.75 Mg C ha^{-1}: vegetation 3.18 (14.62%), saturated soil 8.53 (39.22%), and unsaturated soil 10.04 (46.16%).	Vegetation biomass and soil carbon	Sarkar and Das (2020)

Charanand, 47-Morakolong, Jaluguti, Chatla and Urmal wetlands	Morigaon district and Kamrup district of Assam	Total organic carbon in water was ranged between 3.46 ± 0.77 to 17.77 ± 0.30 mg L^{-1} and Total inorganic carbon in water was ranged between 2.24 ± 0.96 to 26.74 ± 5.52 mg L^{-1}, while soil C was highest in Chatla (6.61%; 5.94%) and Urmal (5.24%; 4.12%) of Kamrup, and lower in Morigaon wetlands- Charan (3.6%; 2.8%), Jaluguti (2.75%; 1.66%), 47–Morakolong (1.30%; 1.00%) with higher values in surface layers.	Water and soil (0-15 and 15-30 cm depth) carbon	Nag et al. (2025)
Chatla wetland	Assam (Barak Valley)	Top 30 cm soil organic carbon reported up to 76.95 t C ha^{-1}	Soil organic carbon (0–30 cm)	Sarkar et al. (2023)
Loktak Lake	Manipur	577.38 ± 58.84 g C m^{-2}	Aquatic macrophytes	Caroline et al. (2024)
Keibul Lamjao National Park		1442.43 ± 276.85 g C m^{-2}		
Thalassery Estuarine Wetland	Kerala	The estimated mean above-ground carbon was 94.63 ± 48.90 t C ha^{-1}, while the mean carbon stock in root and sediment was 41.53 ± 20.24 t C ha^{-1} and 17.48 ± 7.30 t C ha^{-1}, respectively	Vegetation above and below ground biomass, carbon and soil carbon	Vinod et al. (2019)
Rudrasagar lake	Tripura	Soil organic carbon stock was 106.1 Mg C ha^{-1} (0–15 cm), 248.4 (15–30 cm), 334.9 (30–45 cm), and 229.8 ± 94.3 (45–100 cm).	Soil organic carbon at 0–15, 15–30, 30–45 and 45–100 cm soil depth	Taran et al. (2023)
Bhitarkanika wetlands	Odisha (Bhitarkanika Wildlife Sanctuary)	Soil organic carbon ranged from 0.24 ± 0.14 to 3.57 ± 0.80 %,	Sediment carbon at 0–10, 10–20, 20–30, 30–40 and 40–50 cm depth	Banerjee et al. (2022)
Pumlen Pat wetland	Manipur (Phumdi wetlands)	14.94 ± 5.73 Mg C ha^{-1}	Total ecosystem carbon	Singh et al. (2025)
Lamphel Pat wetland		5.24 ± 1.83 Mg C ha^{-1}		
Zaimeng Pat wetland		4.06 ± 1.59 Mg C ha^{-1}		
Mahanadi Mangrove Wetland	Odisha	Mean overall carbon stock: 147.0 ± 8.1 Mg C ha^{-1-1}; natural stands: 143.4 ± 8.2 Mg C ha^{-1-1}; plantation stands: 151.5 ± 7.9 Mg C ha^{-1-1}	Vegetation carbon (89.4 ± 7.6 Mg C ha^{-1}) and soil carbon (57.6 ± 3.2 Mg C ha^{-1}) in surface soil (0–30 cm)	Sahu et al. (2016)
Mangrove forests of the Andaman Islands	Andaman and Nicobar Islands	Mean vegetation carbon stock: 290.26 ± 24.75 Mg C ha^{-1-1}	Vegetation carbon (above-ground biomass and below-ground biomass-carbon)	Ragavan et al. (2021)
Gulf of Kutch mangroves	Gujarat	Vegetation carbon stock: 54.1 Mg C ha^{-1}; soil carbon stock: 25.87 Mg C ha^{-1}	Vegetation and soil carbon.	Sigamani et al. (2023)
Pichavaram mangrove forest (natural and restored stands)	Tamil Nadu	Soil organic carbon stock in 0–90 cm soil depth ranged from 57.41 to 146.10 Mg C ha^{-1}.	Soil organic carbon, 0–90 cm depth	Gnanamoorthy et al. (2019)
Sambhar Lake	Rajasthan	Soil organic carbon stock: 143.17 ± 55.79 t C ha^{-1} (post-monsoon) and 118.69 ± 35.23 t C ha^{-1} (pre-monsoon)	Soil organic carbon up to 0–50 cm depth	Kumar and Sharma (2025)
Keoladeo National Park wetland		Soil organic carbon stock: 251.35 ± 64.35 t C ha^{-1} (post-monsoon) and 164.09 ± 61.78 t C ha^{-1} (pre-monsoon)	Soil organic carbon up to 0–50 cm depth	

Carbon stock and burial varied among riverine, estuarine and marine mangrove settings and were reduced in mangrove areas converted to aquaculture. Studies from the Pichavaram mangrove area on the south-east coast indicate that sequestration varies with restoration history, species, stand age, growth and season (Gnanamoorthy et al. 2019). At Purbasthali oxbow (freshwater) lake, the average methane-adjusted net carbon sequestration was estimated at 13.96 ± 8.35 t CO_2e ha^{-1} yr^{-1}, although substantial pre-monsoon, monsoon and post-monsoon seasonal variation occurred (Das et al. 2025), with the highest total carbon storage recorded during the post-monsoon season (657.91 ± 19.71 g C m^{-2} yr^{-1}; 2411.88 ± 72.26 g CO_2e m^{-2} yr^{-1}). Spatial modelling further identified areas with carbon sequestration values ranging from 1510.58 to 1959.66 g CO_2e m^{-2} yr^{-1} in the eastern agricultural zone of the wetland. Sen et al. (2024) reported that the East Kolkata Wetlands exhibited seasonal variation in soil carbon sequestration, with the highest rates during the post-monsoon (208.33–251.28 g C m^{-2} yr^{-1}), followed by the pre-monsoon (147.21–191.36 g C m^{-2} yr^{-1}) and the monsoon season (89.14–169.70 g C m^{-2} yr^{-1}). The corresponding average carbon sequestration potentials were 846.85, 623.00, and 476.54 g CO_2e m^{-2} yr^{-1} during winter, summer, and the monsoon, respectively. Existing studies are concentrated in a limited number of wetland types and differ substantially in the carbon pools assessed, monitoring duration and calculation methods. Accordingly, future assessments should prioritize repeated stock measurements, sediment-accumulation methods and direct greenhouse-gas monitoring within common experimental frameworks rather than extrapolating sequestration from standing carbon stocks.

Table 2: Reported carbon sequestration rates of Indian wetlands.

Wetland site	**Wetland type**	**Pool**	**Reported rate**	**Reference**
Sundarbans wetland area of India	Natural mangrove	Live-biomass and sediment	4.71–6.54 Mg C ha^{-1} yr^{-1}; live biomass (1.69 Mg C ha^{-1} yr^{-1}) and sediment (0.012 Mg C ha^{-1} yr^{-1})	Ray et al. (2011)
Kochi mangroves	Fragmented natural mangrove	Living and dead biomass and Sediment (Soil) carbon sequestration	2.95 Mg C ha^{-1} yr^{-1}; dead biomass (7.12± 2.81 t C ha^{-1} yr^{-1}); The CO_{2e} of ecosystem carbon stock (496311.20 t CO_2 e) and soil CO_2 burial (10.62 t CO_2 e ha^{-1} yr^{-1} respectively)	Rani et al. (2023)
Pichavaram mangrove forest.	Natural and restored mangroves	Soil-carbon sequestration	2.33 to 4.44 g C m^{-2} $year^{-1}$	Gnanamoorthy et al. (2019)
Tropical Floodplain Wetlands, Assam	Natural	Vegetation carbon sequestration	6.36 Mg C ha^{-1} $year^{-1}$	Sarkar and Das (2020)
East Kolkata Wetland	Sewage-fed urban wetland	Seasonal soil carbon sequestration	Soil carbon stock (at 0-15 cm depth) ranged 147.21–191.36 g m^{-2} yr^{-1} in pre-monsoon, 89.14–169.70 g m^{-2} yr^{-1} in monsoon, and 208.33–251.28 g m^{-2} yr^{-1} in post-monsoon	Sen et al. (2024)
Purbasthali oxbow lake	Restored freshwater wetland	CH_4-adjusted net sequestration	13.96 ± 8.35 t CO_2e ha^{-1} yr^{-1}	Das et al. (2025)

3.5 Drivers of wetland carbon sequestration: The large variability in carbon stocks and sequestration rates reported among Indian wetlands cannot be explained by wetland type alone.

Carbon accumulation is the net outcome of multiple interacting controls that regulate primary productivity, the availability and inputs of organic matter, rates of decomposition, sediment burial and gaseous losses. In wetland ecosystems, hydrology also influences vegetation and soil carbon availability, redox conditions, microbial metabolism and sediment transport, which together affect carbon inputs, decomposition, burial and greenhouse gas emissions. Wetland hydrology is a key component because water-table depth, soil moisture, flooding duration and connectivity regulate oxygen availability, decomposition and greenhouse gas production. Prolonged waterlogging generally favors carbon preservation, while drainage can enhance CO_2 release and alter CH_4 dynamics (Cui et al., 2024). Vegetation contributes carbon through litter, roots and plant residues, with mangroves storing large amounts in woody biomass and grasses and macrophytes contributing substantially below ground. Soil texture, mineral composition, pH, nutrients and sediment deposition further influence carbon stabilization and long-term burial. Climate and monsoon seasonality affect both plant productivity and microbial activity by altering temperature, rainfall, inundation and sediment inputs. In coastal wetlands, salinity and tidal exchange influence sediment supply and microbial processes. Anthropogenic activities such as drainage, vegetation disturbance and removal, and nutrient enrichment can substantially affect the rate of carbon sequestration, either by reducing stored carbon or by increasing greenhouse gas emissions. Therefore, wetland carbon sequestration should be understood as a dynamic ecosystem process shaped by interacting environmental and anthropogenic controls (Baiswar et al., 2026).

4. Conclusion

Indian wetlands function as significant carbon sinks, storing and sequestering carbon across multiple interconnected pools including soils and sediments, above- and belowground vegetation biomass, and the water column. However, the available literature is dominated by one-time stock assessments, and relatively few studies have directly quantified annual carbon sequestration. Evidence from different wetland ecosystems, such as mangroves, floodplains, freshwater lakes, and coastal wetlands, shows considerable variability in carbon storage potential influenced by ecological, hydrological, climatic, and other factors. Soil organic carbon and plant biomass constitute the dominant and most extensively studied carbon reservoirs; however, aquatic macrophytes and dissolved inorganic carbon in the water also represent ecologically important carbon pools that remain systematically under-studied in the Indian context. Despite their recognized importance in ecosystem services and climate change mitigation, critical gaps persist in the systematic assessment of wetland carbon stocks, standardization of measurement methodologies, and long-term monitoring of carbon fluxes at the national scale. Bridging these knowledge gaps through rigorous, multi-ecosystem research is imperative to accurately quantify the carbon sequestration capacity of Indian wetlands and to meaningfully integrate them into national climate change mitigation frameworks and evidence-based wetland conservation and management policy formulation. Future assessments should also combine repeated carbon inventories, sediment-accumulation measurements and CO_2, CH_4 and N_2O flux monitoring within representative wetland classes.

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