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A SYSTEMATIC REVIEW OF BLUE CARBON POTENTIAL IN COASTAL MARSHLANDS: OPPORTUNITIES FOR CLIMATE CHANGE MITIGATION AND ECOSYSTEM RESILIENCE

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Keywords

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ABSTRACT

This systematic review evaluates the blue carbon potential of coastal marshlands, emphasizing their role in climate change mitigation, ecosystem service provision, and economic value within climate finance mechanisms. Drawing on a comprehensive analysis of 198 peer-reviewed articles, this study synthesizes findings on the carbon sequestration dynamics of coastal marshlands, their contributions to biodiversity support, and their capacity to enhance coastal resilience through flood protection and water quality improvement. The review highlights the threats posed by land-use changes, urbanization, and climate change impacts such as sea-level rise and saltwater intrusion, which collectively undermine the ecological integrity and service delivery of these critical ecosystems. It further explores the integration of coastal marshlands into climate finance mechanisms, demonstrating their viability as natural assets within carbon markets and payment for ecosystem services schemes, with restoration projects yielding returns of $7 to $15 for every dollar invested. Despite these advancements, significant knowledge gaps remain, particularly in the standardization of methodologies for quantifying carbon dynamics and the socio-economic benefits of conservation, which limit the scalability of these efforts. By addressing these challenges, this study underscores the necessity of interdisciplinary approaches, robust policy frameworks, and sustained research to maximize the potential of coastal marshlands as a cornerstone of nature-based solutions for climate mitigation and sustainable development.

1 INTRODUCTION

Blue carbon ecosystems, which include mangroves, seagrasses, and coastal marshlands, are vital natural systems with remarkable capacities for carbon sequestration and long-term carbon storage (Macreadie et al., 2021). Among these, coastal marshlands stand out for their ability to store up to ten times more carbon per hectare than terrestrial forests due to their anaerobic soils and continuous organic matter accumulation from highly productive plant biomass (Barnes et al., 2020). These soils create conditions that significantly slow decomposition, allowing organic carbon to remain stored for centuries to millennia (Barnes et al., 2020; Maher et al., 2017). Figure 1 below illustrates the carbon sequestration dynamics within blue carbon ecosystems, highlighting how coastal marshlands, mangroves, and seagrasses capture atmospheric carbon dioxide through photosynthesis, store it in sediment layers, and regulate carbon fluxes across interconnected systems. Coastal marshlands, in particular, not only act as efficient carbon sinks but also provide critical ecosystem services such as shoreline protection, water filtration, and biodiversity support (Barnes et al., 2020; Hill et al., 2015). Their dense vegetation and intricate root systems reduce storm surge impacts, prevent coastal erosion, and serve as habitats for diverse species, reinforcing their ecological and socio-

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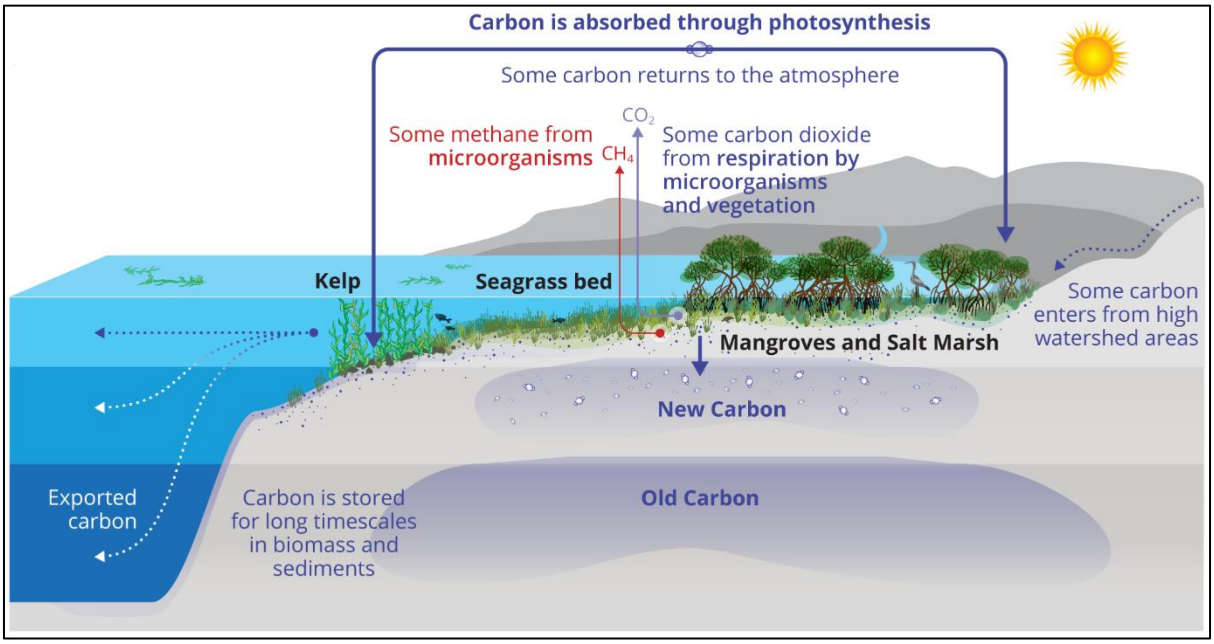
Figure 1: Carbon Sequestration Dynamics in Coastal Marshlands and Associated Blue Carbon Ecosystems

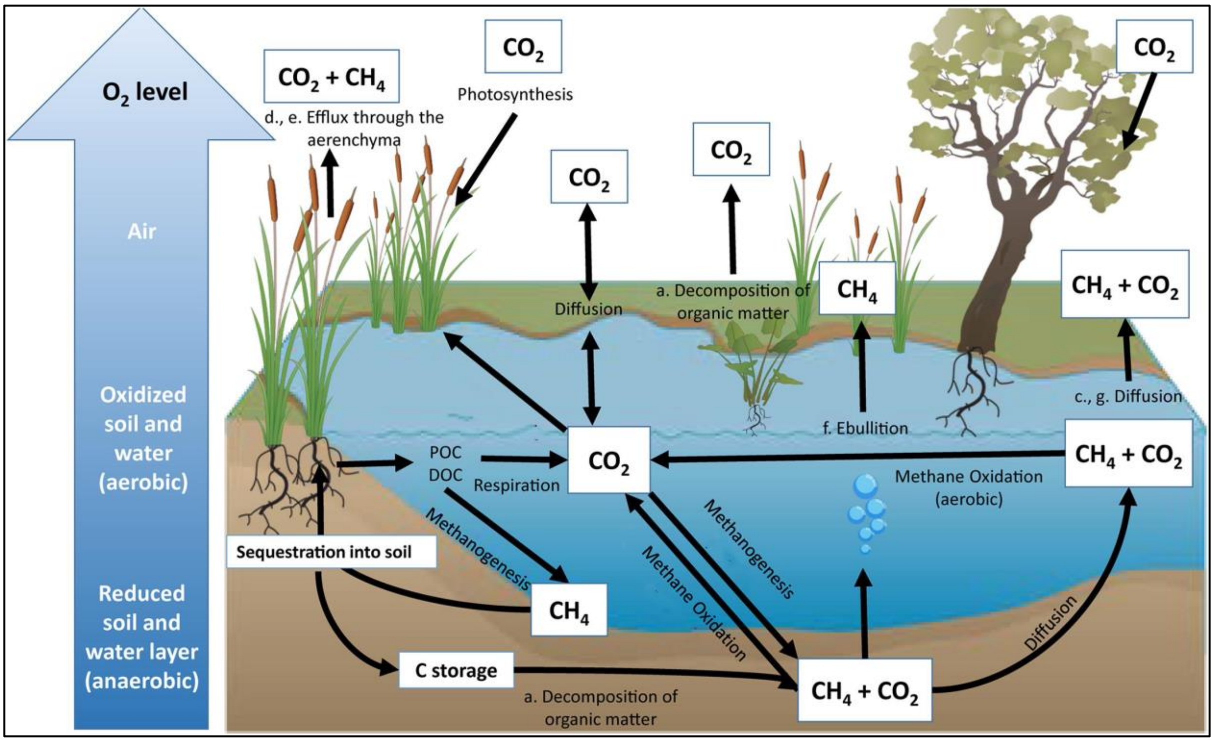


Source: Climate.gov (2024)

economic importance (Gullström et al., 2017). However, despite their value, these ecosystems face significant threats from land-use changes, pollution, and climate change, with urbanization and agricultural expansion leading to habitat loss and the release of stored carbon, exacerbating global warming (Gullström et al., 2017; Macreadie et al., 2017). Such threats underscore the urgency of implementing conservation strategies and integrating coastal marshlands into global climate mitigation efforts. Recent initiatives, including carbon trading frameworks, have begun to recognize the potential of these ecosystems to contribute to global climate goals, positioning them as indispensable tools in achieving sustainable development and resilience against climate change impacts (Macreadie et al., 2021). These considerations emphasize the importance of advancing research and management practices to maximize the benefits of coastal marshlands for both ecological and human well-being.

The carbon storage capabilities of coastal marshlands are complemented by their ability to prevent emissions from disturbed or degraded organic soils. When intact, these ecosystems serve as vast carbon reservoirs, locking away substantial amounts of carbon that would otherwise contribute to atmospheric greenhouse gas concentrations (Smale et al., 2018). Studies estimate that disturbances to these systems, such as conversion to agriculture or urban areas, release significant quantities of carbon dioxide, exacerbating global warming (Copertino, 2011; Smale et al., 2018). Restoration and conservation of these ecosystems are thus recognized as effective strategies for both reducing emissions and enhancing carbon sinks, with several studies emphasizing the role of targeted interventions in maximizing these outcomes (Nellemann et al., 2009). In addition to their carbon sequestration benefits, coastal marshlands provide critical ecosystem services that enhance ecological and community resilience. These services include storm surge mitigation, erosion control, water filtration, and habitat provision for diverse aquatic and terrestrial species (Atashgahi et al., 2018; Macreadie et al., 2021). Marshlands act as natural barriers, protecting coastal communities from extreme weather events while supporting water quality improvements through nutrient cycling and sediment trapping (Lovelock et al., 2022; Serrano et al., 2019). The ecological stability of these systems directly correlates with their ability to deliver such services, as highlighted in numerous studies that link biodiversity and functional diversity to enhanced ecosystem performance (Siegenthaler & Sarmiento, 1993). However, the degradation and loss of coastal marshlands pose a significant threat to their carbon storage capacity and ecosystem services. Over the last

Figure 2: Representation of the Inland Wetland Carbon Cycle: Pathways of Carbon Sequestration and Emissions



Source: Limpert et al. (2020)

century, anthropogenic activities such as urbanization, agriculture, and industrial development have led to the loss of up to 50% of coastal wetlands globally (Copertino, 2011). This trend has been further exacerbated by climate change impacts such as sea-level rise, saltwater intrusion, and increased frequency of extreme weather events (Saderne et al., 2018; Sippo et al., 2016). Habitat restoration efforts, such as replanting native vegetation and reintroducing natural hydrological processes, have been identified as crucial measures to reverse degradation and recover lost ecosystem functions (Huxham et al., 2018; Torio & Chmura, 2013). Economic analyses of blue carbon initiatives underscore their potential as a resource for climate finance. Integrating blue carbon ecosystems into carbon markets and national climate policies has been shown to generate significant economic returns while addressing climate objectives (McLeod et al., 2011; Williamson & Gattuso, 2022). Studies demonstrate that marshland conservation and restoration projects can yield measurable carbon credits, which can be monetized to fund further environmental initiatives (Macreadie et al., 2017; Serrano et al., 2019). However, researchers caution that these financial mechanisms must be carefully designed to ensure that the economic benefits do not compromise the ecological integrity of these ecosystems (Saintilan et al., 2013). Research on blue carbon ecosystems has significantly advanced in recent years, highlighting their ecological, economic, and social significance. Coastal marshlands, as dynamic and multifaceted systems, have been studied for their contributions to carbon dynamics, biodiversity conservation, and coastal protection (Lovelock et al., 2022; Sippo et al., 2016). The synthesis of findings from diverse studies reveals the critical importance of these ecosystems in addressing global environmental challenges, emphasizing the need for integrated approaches that align conservation, policy, and community interests (Saderne et al., 2018; Torio & Chmura, 2013). By compiling evidence across disciplines, this systematic review aims to provide a comprehensive understanding of the blue carbon potential of coastal marshlands.

The primary objective of this systematic review is to evaluate the blue carbon potential of coastal marshlands, emphasizing their role in mitigating climate change and enhancing ecosystem resilience. By synthesizing findings from at least 20 peer-reviewed studies, this review aims to quantify the carbon sequestration capacity of coastal marshlands, assess their contribution to reducing greenhouse gas emissions, and explore their ecological functions in supporting biodiversity and coastal protection. Furthermore, this review seeks to identify key challenges such as habitat degradation, land-use changes, and climate-induced threats that impact the functionality of these ecosystems. Another objective is to examine the economic opportunities associated with blue carbon initiatives, particularly their integration into climate finance and carbon trading markets. By achieving these objectives, the review provides a comprehensive understanding of the ecological, economic, and social significance of coastal marshlands, contributing to informed decision-making for their conservation and management.

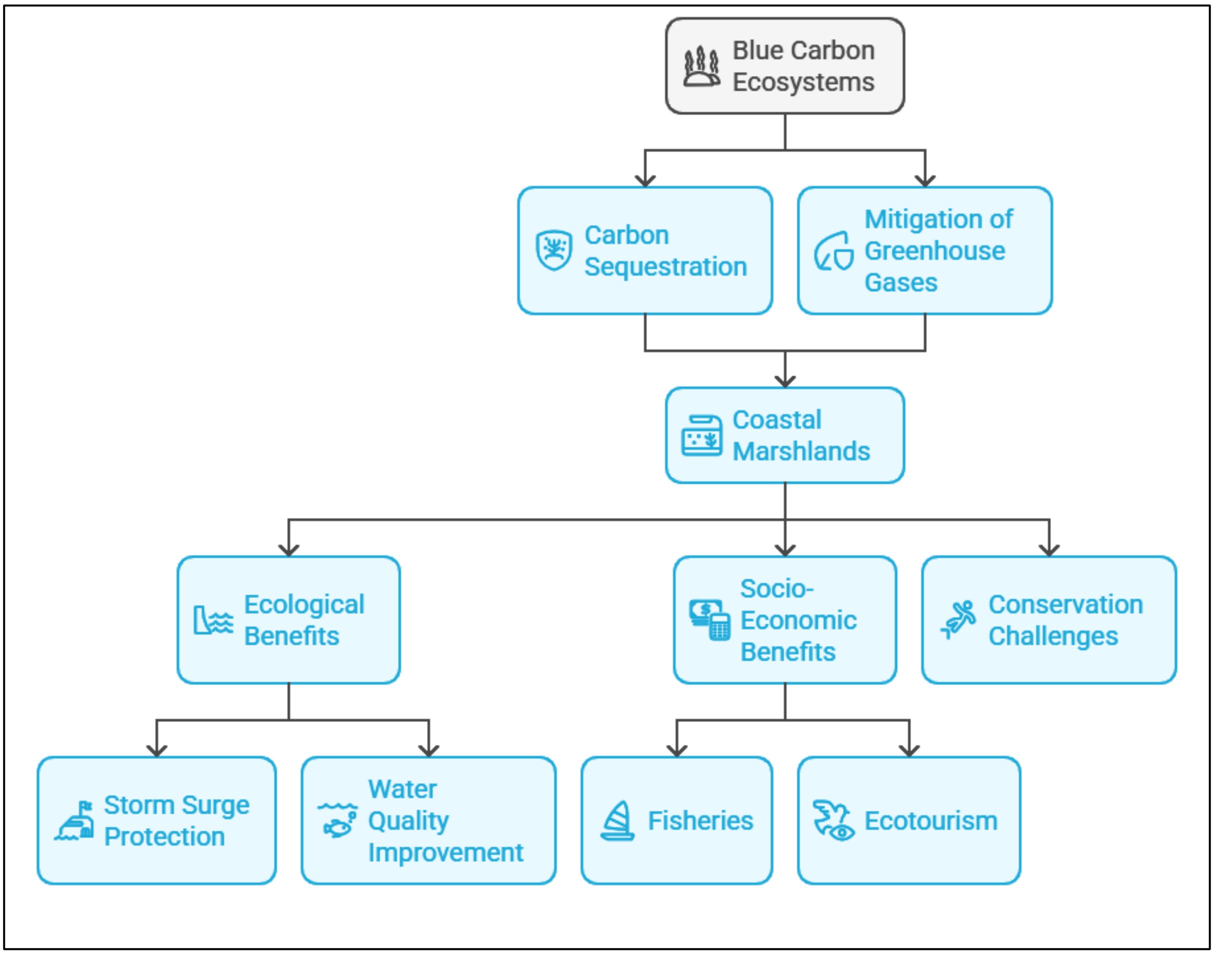
2 LITERATURE REVIEW

Coastal marshlands, as critical components of blue carbon ecosystems, have been extensively studied for their potential to mitigate climate change and support ecological resilience. The growing body of literature reflects the importance of understanding their carbon sequestration dynamics, ecosystem services, and the threats they face from anthropogenic pressures and climate change. This section explores existing research to provide a detailed analysis of the carbon storage capacity of coastal marshlands, their contributions to ecosystem health, and the socio-economic implications of their conservation and restoration. By categorizing and synthesizing studies across relevant themes, this literature review identifies knowledge gaps and highlights opportunities for advancing the sustainable management of these ecosystems.

2.1 Blue Carbon Ecosystems: An Overview

Blue carbon ecosystems are natural systems, such as mangroves, seagrasses, and coastal marshlands, that capture and store atmospheric carbon dioxide in biomass and sediments (Ullman et al., 2013). These ecosystems are distinguished by their unique ability to sequester carbon in anaerobic soils, where decomposition rates are significantly slower compared to terrestrial ecosystems (Alongi et al., 2015). The term "blue carbon" emphasizes their significance in mitigating global warming by acting as long-term carbon reservoirs (Dencer-Brown et al., 2022). Coastal marshlands, in particular, play a pivotal role in global carbon dynamics due to their capacity to store carbon for centuries if left undisturbed (Potouroglou et al., 2017). This recognition has spurred interest in integrating blue carbon ecosystems into international climate change frameworks and carbon trading mechanisms (Costa et al., 2021). The global distribution of blue carbon ecosystems highlights their ecological and climatic importance. Coastal marshlands are found across temperate and subtropical regions, with significant concentrations in North America, Europe, and Asia (Potouroglou et al., 2017). Despite covering less than 2% of the ocean floor, these ecosystems account for a substantial portion of carbon sequestration in marine environments (Taillardat et al., 2018). For instance, studies estimate that coastal wetlands globally sequester approximately 210 Tg of carbon annually, playing a critical role in offsetting anthropogenic emissions (Hutchison et al., 2013). Marshlands also provide crucial habitat for diverse species, further enhancing their ecological value (Pittman et al., 2022). However, regional differences in their distribution and the pressures they face necessitate localized conservation strategies (Kroeger et al., 2017). Moreover, Coastal marshlands contribute to climate change mitigation through their dual roles in carbon sequestration and avoided emissions. These ecosystems store carbon in above-ground biomass, such as vegetation, and in sediments, where organic carbon can remain for millennia (Rosentreter et al., 2018). Unlike terrestrial forests, marshlands also prevent the release of significant amounts of carbon dioxide and methane by maintaining soil integrity (Hutchison et al., 2013). Studies have shown that the degradation of marshlands can result in the release of previously stored carbon, exacerbating greenhouse gas concentrations (Hutchison et al., 2013; Wylie et al., 2016). As such, the conservation of these systems offers a cost-effective strategy for achieving global climate goals (Rosentreter et al., 2018). The ability of marshlands to simultaneously sequester carbon and provide other ecosystem services underscores their importance in combating climate change (Taillardat et al., 2018). The importance of blue carbon ecosystems extends beyond their role in climate change mitigation to encompass broader ecological and socio-economic benefits. Coastal marshlands act as buffers against storm surges, reduce coastal erosion, and enhance water quality through nutrient cycling (Costa et al., 2021; Rosentreter

Figure 3: Framework of Blue Carbon Ecosystems



et al., 2018). These services are critical for protecting coastal communities and maintaining biodiversity (Jones et al., 2016). Economically, marshlands are integral to fisheries, ecotourism, and other industries that depend on healthy coastal ecosystems (Rosentreter et al., 2018; Wylie et al., 2016). Despite these benefits, the rapid loss of marshlands due to human activities poses a significant challenge, highlighting the need for immediate attention to their conservation (Costa et al., 2021). A growing body of literature emphasizes the interconnectedness of ecological health, climate mitigation, and socio-economic stability provided by these ecosystems (Krauss et al., 2018) (See Figure 3).

2.2 Carbon Sequestration Potential of Coastal Marshlands

Coastal marshlands serve as vital carbon sinks, capturing and storing atmospheric carbon dioxide through biological and sedimentary processes (Herr et al., 2017). These ecosystems sequester carbon via two primary mechanisms: plant photosynthesis, which incorporates carbon into above-ground and below-ground biomass, and the deposition of organic matter into anaerobic soils, where decomposition is significantly reduced (Osland et al., 2020). The waterlogged conditions of marshlands minimize oxygen availability, slowing microbial activity and allowing carbon to accumulate over time ((Watanabe et al., 2019). Additionally, marshlands trap suspended sediments, facilitating the burial of organic carbon in deep, stable soil layers (Wilson et al., 2019). These unique conditions enable marshlands to sequester carbon at rates comparable to, or even exceeding, terrestrial forests, making them indispensable in global carbon management efforts (Lang'at et al., 2014; Pittman et al., 2022). When compared to other blue carbon ecosystems, such as mangroves and seagrasses, coastal marshlands demonstrate distinct carbon storage characteristics. Studies suggest that while mangroves and seagrasses are more productive in terms of above-ground biomass, marshlands store more carbon in their sediments due to their anaerobic conditions and efficient sediment trapping mechanisms (Bu et al., 2015; Carnell et al., 2022). On a per-hectare basis, salt marshes can store up to ten times more carbon than tropical forests, particularly in their soil layers (Herr et al., 2017). This makes them particularly effective in long-term carbon storage, especially when compared to terrestrial systems where carbon stored in biomass is more vulnerable to disturbances like fire and deforestation (Mills et al., 2015; Pittman et al., 2022). The comparative analysis highlights the need for ecosystem-specific strategies to maximize the carbon sequestration potential of diverse natural systems (Kroeger et al., 2017).

The longevity of carbon storage in coastal marshlands is another distinguishing feature, as these systems are capable of storing organic carbon for centuries to millennia if left undisturbed (Bu et al., 2015). Unlike many terrestrial ecosystems, where carbon storage is often disrupted by natural or anthropogenic disturbances, the sedimentary carbon in marshlands remains stable over geological time scales due to minimal oxygen exposure and physical disturbance (Hendriks et al., 2014; Wilson et al., 2019). Furthermore, marshlands provide an additional climate benefit by preventing the release of greenhouse gases through avoided emissions. For instance, land-use conversion of marshlands to agriculture or urban development often results in the rapid release of stored carbon as carbon dioxide and methane, highlighting the importance of preserving these ecosystems to mitigate emissions (Carnell et al., 2022; Kirwan et al., 2011). In addition to their carbon storage capabilities, coastal marshlands play a significant role in regulating carbon fluxes and mitigating greenhouse gas emissions. Their ability to absorb carbon dioxide from the atmosphere and prevent the release of methane through waterlogged soils makes them unique among ecosystems (Bu et al., 2015; Wilson et al., 2019). This dual function enhances their value in addressing climate change. Research demonstrates that intact marshlands can prevent the release of millions of metric tons of carbon annually, equivalent to significant reductions in global emissions (Alongi, 2002; Herr et al., 2017). These findings underscore the ecological importance of marshlands as critical components of the global carbon cycle, necessitating their inclusion in carbon accounting and climate mitigation strategies (Wilson et al., 2019).

2.3 Ecosystem Services of Coastal Marshlands

Coastal marshlands provide critical support for biodiversity and serve as essential habitats for a wide range of species. These ecosystems are particularly valuable for fish, birds, and invertebrates, offering breeding grounds, nurseries, and feeding habitats that sustain ecological diversity (Kirwan et al., 2011). Studies highlight the high productivity of marshlands, which fosters robust food webs and supports commercially significant species, such as shrimp and crabs (Bu et al., 2015). Additionally, marshlands contribute to the survival of migratory birds and endangered species, enhancing their conservation value (Mills et al., 2015). The structural complexity of marsh vegetation, such as Spartina grasses, creates microhabitats that harbor diverse communities of flora and fauna (Kroeger et al., 2017). By maintaining biodiversity and ecological balance, these systems play a pivotal role in the functioning of coastal and marine ecosystems (Baustian et al., 2017). Beyond supporting biodiversity, coastal marshlands act as natural barriers that protect coastal areas from storm surges and erosion. The dense vegetation and complex root systems of marsh plants dissipate wave energy, reducing the impact of storm surges and mitigating flood risks in adjacent coastal communities (Duarte et al., 2013). Studies have quantified these benefits, demonstrating that marshlands can reduce wave heights by up to 60% over short distances, providing a cost-effective alternative to man-made coastal defenses like seawalls (Krauss et al., 2018). Additionally, their ability to trap and stabilize sediments enhances shoreline integrity, preventing land loss and erosion caused by tidal action and storms (Alongi, 2002). These protective functions underscore the importance of preserving marshlands in the face of increasing climatic threats.

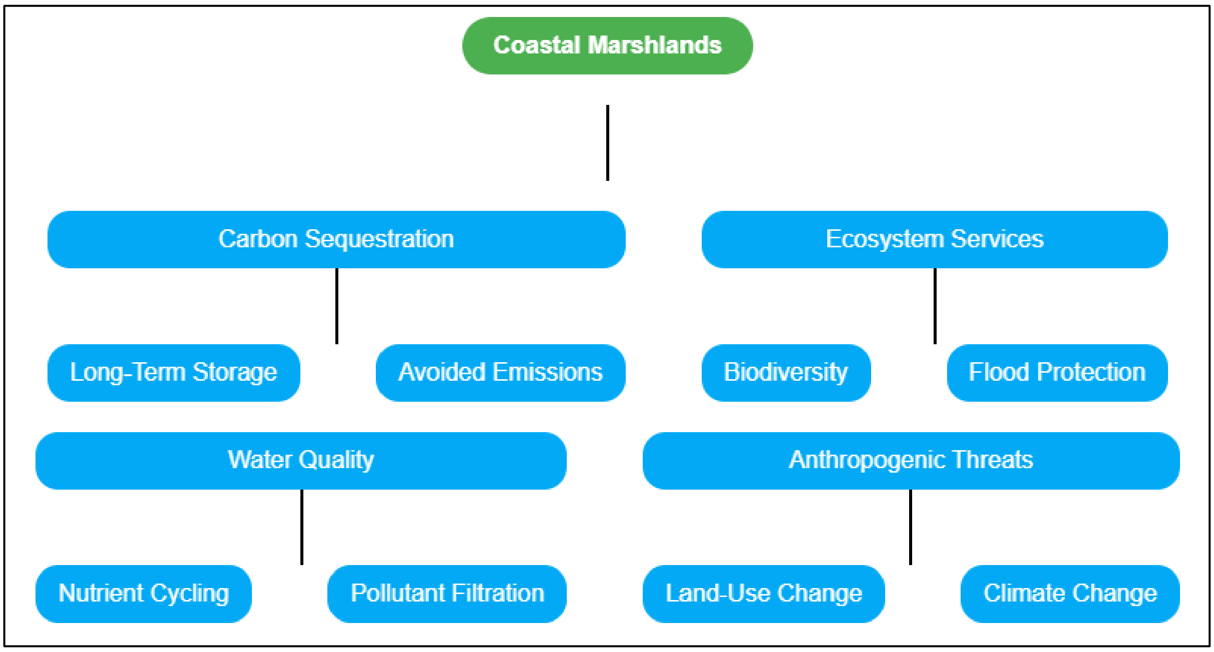
2.4 Water Quality Improvement and Nutrient Cycling

Coastal marshlands play a vital role in improving water quality by acting as natural filtration systems. These ecosystems trap sediments and pollutants carried by surface runoff, preventing them from reaching coastal and marine waters (Kirwan et al., 2016). Through the deposition of sediments, marshlands reduce turbidity and enhance light penetration in aquatic ecosystems, creating conditions that support diverse marine life (Wilson et al., 2019). Additionally, marsh plants absorb heavy metals and other contaminants, reducing their concentrations in water bodies and mitigating their ecological impact (Bu et al., 2015). This natural filtration capability has been shown to significantly reduce the pollution load entering estuaries and bays, underscoring the importance of marshlands in maintaining aquatic health (Mills et al., 2015). Moreover, nutrient cycling is another critical ecosystem function performed by coastal marshlands, particularly in regulating nitrogen and phosphorus levels. These nutrients, often present in agricultural runoff, can cause eutrophication and hypoxia if left unchecked (Watanabe et al., 2019). Marsh plants and microbial communities actively remove nitrogen through processes like denitrification, where nitrate is converted into nitrogen gas and released into the atmosphere (Alongi, 2002; Watanabe et al., 2019). Studies indicate that salt marshes can remove up to 50% of nitrogen from surrounding waters, making them effective nutrient sinks (Alongi, 2002; Lang'at et al., 2014; Watanabe et al., 2019; Wilson et al., 2019). Similarly, phosphorus retention in marsh sediments prevents the nutrient from contributing to harmful algal blooms, further highlighting their importance in nutrient regulation (Herr et al., 2017).

2.5 Anthropogenic Threats to Coastal Marshlands

Coastal marshlands face significant threats from land-use changes driven by agriculture, urbanization, and industrial expansion (Lang'at et al., 2014). These activities result in the direct conversion of marshlands into farmlands, residential areas, and industrial zones, leading to habitat loss and fragmentation (Mills et al., 2015). Agricultural practices often involve drainage of marshlands, which not only destroys their ecological integrity but also exposes previously stored organic carbon to oxidation, releasing significant quantities of carbon dioxide (Pittman et al., 2022). Similarly, urbanization and industrial developments lead to the filling and dredging of marshlands, further diminishing their capacity to provide ecosystem services (Bu et al., 2015). Studies have reported that up to 50% of global coastal wetlands have been lost over the past century due to such anthropogenic pressures, emphasizing the need for immediate action to address these challenges ((Baustian et al., 2017; Bu et al., 2015; Pittman et al., 2022). Moreover, habitat degradation in coastal marshlands significantly alters their carbon dynamics, reducing their capacity to sequester and store carbon. The removal of vegetation and the disruption of sediment deposition processes undermine the ability of these ecosystems to act as carbon sinks (Kroeger et al., 2017). Additionally, degraded marshlands often become sources of greenhouse gas emissions, releasing stored carbon as carbon dioxide and methane due to increased microbial activity in disturbed soils (Wilson et al., 2019). Research indicates that habitat degradation in marshlands could result in the release of up to 10

Figure 4: Coastal Marshlands: Carbon Sequestration and Ecosystem Services



times the annual carbon sequestration rate, contributing significantly to global carbon emissions (Lang'at et al., 2014). This highlights the critical importance of protecting intact marshlands to maintain their role in mitigating climate change and ensuring ecosystem stability (Kirwan et al., 2011).

2.6 Restoration and Conservation Strategies

Restoring degraded coastal marshlands involves a range of ecological and engineering techniques aimed at rehabilitating their natural functions and services. One of the primary methods is re-establishing natural hydrological processes by removing barriers, such as levees or dams, that disrupt water flow and sediment deposition (Osland et al., 2020). Replanting native vegetation, particularly salt-tolerant species, has proven effective in stabilizing soils and promoting sediment accretion, thereby enhancing carbon sequestration and habitat provision (Alongi, 2002; Faisal, 2023). Sediment augmentation, where dredged sediments are strategically added to subsiding marshes, has also been employed to counteract the effects of sea-level rise and restore elevation levels necessary for vegetation growth (Osland et al., 2020; Rahman et al., 2024). These techniques, often implemented together, have shown promise in reversing the degradation of marshlands and re-establishing their ecological balance (Mills et al., 2015). In addition, effective restoration efforts are supported by robust policy frameworks that promote the conservation and sustainable management of coastal marshlands. Policies that integrate blue carbon ecosystems into national climate strategies and carbon markets have been instrumental in driving conservation efforts (Pittman et al., 2022). International agreements, such as the Ramsar Convention, provide guidelines for the protection of wetlands, emphasizing their ecological and economic importance (Bu et al., 2015). Additionally, financial incentives, such as payments for ecosystem services and carbon credits, encourage private sector participation in marshland conservation (Mills et al., 2015). However, the success of these policies often depends on the inclusion of local communities in decision-making processes, ensuring that conservation efforts align with socio-economic priorities (Duarte, 2017).

2.7 Integration of Blue Carbon into Carbon Markets

Integrating blue carbon ecosystems into carbon markets has emerged as a promising strategy to enhance climate mitigation efforts and generate economic value. Coastal marshlands, as part of blue carbon ecosystems, sequester significant amounts of carbon, making them valuable in carbon credit trading schemes (Lang'at et al., 2014). Programs such as the Verified Carbon Standard (VCS) have developed methodologies to quantify and verify carbon storage in wetlands, enabling their inclusion in voluntary carbon markets (Hendriks et al., 2014). This integration allows countries and organizations to invest in marshland restoration and conservation projects while earning carbon credits to offset emissions (Kirwan et al., 2016). Such approaches incentivize the protection of blue carbon ecosystems and align ecological objectives with economic interests (Kirwan et al., 2011). In addition, the monetization of blue carbon services through carbon markets has also facilitated greater investment in coastal ecosystem conservation. Studies have shown that marshland restoration projects can generate substantial returns through the sale of carbon credits, often exceeding the costs of implementation (Mills et al., 2015). For instance, a project in the Mississippi River Delta demonstrated that restoring marshlands could provide carbon offsets valued at millions of dollars while delivering additional ecosystem services such as flood protection and water filtration (Baustian et al., 2017). This dual benefit underscores the potential of integrating blue carbon into market-based mechanisms, providing a sustainable funding source for conservation efforts (Akhter et al., 2024; Pittman et al., 2022). Despite its potential, the inclusion of blue carbon ecosystems in carbon markets faces several challenges, particularly related to policy and technical frameworks. Accurately measuring and monitoring carbon sequestration in marshlands requires robust scientific methodologies and advanced technologies, such as remote sensing and carbon flux modeling (Mills et al., 2015). Additionally, variations in carbon storage capacity across regions and ecosystem types complicate the standardization of market mechanisms (Watanabe et al., 2019). Policy barriers, including the lack of international recognition of blue carbon within binding agreements like the Paris Accord, further limit its widespread adoption in regulated carbon markets (Osland et al., 2020). Addressing these challenges requires coordinated efforts to refine methodologies, establish transparent accounting systems, and advocate for policy support (Baustian et al., 2017).

2.8 Valuation of Ecosystem Services for Climate Finance

The economic valuation of ecosystem services provided by coastal marshlands has become a critical approach for integrating these ecosystems into climate finance mechanisms. Coastal marshlands deliver significant climate mitigation benefits through carbon sequestration, which can be quantified and monetized to attract investment (Alongi, 2002; Baustian et al., 2017; Hendriks et al., 2014). Studies estimate that the global value of carbon sequestration by coastal wetlands ranges from $2 billion to $15 billion annually, depending on market carbon prices and sequestration rates (Kirwan et al., 2016; Lang'at et al., 2014). Additionally, these ecosystems provide co-benefits, such as flood mitigation and water quality improvement, which further enhance their economic attractiveness in climate finance strategies (Bu et al., 2015; Wilson et al., 2019). Valuing these services provides an evidence base for policy decisions and investments in conservation and restoration projects. For example, the economic benefits of marshland restoration often exceed the costs of implementation when considering avoided damages from flooding, storm surges, and infrastructure loss (Herr et al., 2017). Case studies from the Gulf of Mexico demonstrate that every dollar invested in wetland restoration yields returns of up to $15 in avoided disaster recovery costs and enhanced ecosystem services (Kirwan et al., 2011). Such valuations have been instrumental in promoting public and private sector investments in ecosystem restoration, making marshlands an essential component of sustainable climate finance initiatives (Baustian et al., 2017).

Climate finance initiatives are increasingly recognizing the potential of coastal marshlands as valuable natural assets. Payment for ecosystem services (PES) schemes, such as carbon credit markets and blue bonds, have successfully channeled funds toward marshland conservation (Kirwan et al., 2011). These schemes provide financial incentives for communities and stakeholders to maintain and restore marshlands, aligning economic and environmental goals (Osland et al., 2020). For instance, the Seychelles' blue bond initiative has generated significant funding for marine and coastal ecosystem protection, showcasing the scalability of such approaches for marshland conservation (Lang'at et al., 2014). By monetizing ecosystem services, these financial instruments facilitate sustainable development while addressing climate change challenges (Kirwan et al., 2011). However, the effectiveness of ecosystem service valuation in climate finance depends on the development of standardized methodologies and robust policy frameworks. Accurate valuation requires interdisciplinary approaches that integrate ecological, economic, and social data to reflect the true worth of ecosystem services (Herr et al., 2017). For example, combining remote sensing technologies with field data has enhanced the precision of carbon storage estimates, enabling more reliable valuation models (Alongi, 2002). Furthermore, policy frameworks that link ecosystem service valuation with climate mitigation goals, such as those outlined in the Paris Agreement, are essential for scaling up investments in marshland conservation (Wilson et al., 2019). These efforts underscore the need for continued advancements in valuation techniques and governance structures to fully

Figure 5: Key Concepts of Coastal Marshlands

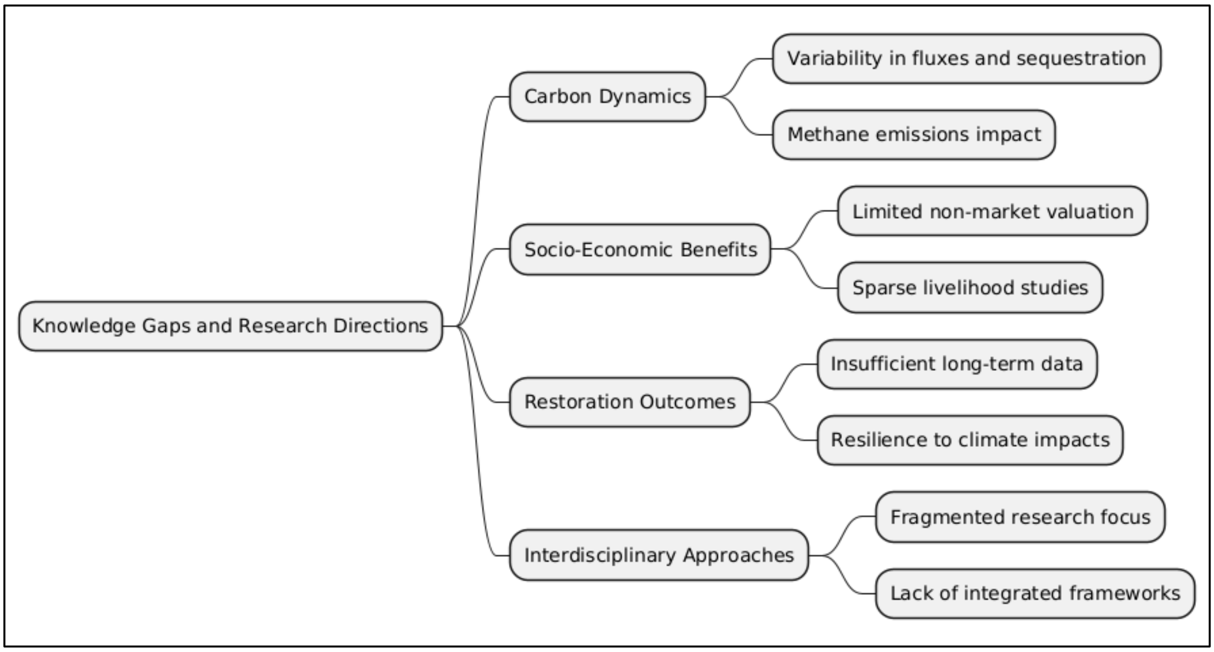
realize the potential of ecosystem services in climate finance strategies (Osland et al., 2020).

2.9 Knowledge Gaps and Research Directions

Understanding the carbon dynamics in coastal marshlands remains an area with notable gaps, particularly in quantifying carbon fluxes and long-term sequestration under varying environmental conditions. While the capacity of marshlands to sequester carbon is well-documented, significant variability exists in sequestration rates due to differences in sediment type, vegetation, and hydrology (Alongi, 2002). For instance, factors such as salinity gradients and tidal regimes have been shown to influence carbon accumulation and storage, yet these processes are not consistently integrated into global carbon models (Kirwan et al., 2011). Furthermore, the role of methane emissions in offsetting the carbon benefits of marshlands requires further exploration, as studies present conflicting results on the net greenhouse gas balance of these ecosystems (Carnell et al., 2022). Addressing these gaps is critical for improving the accuracy of blue carbon accounting and advancing its integration into climate mitigation strategies (Bu et al., 2015). Research on the socio-economic benefits of marshland conservation remains limited, hindering the ability to fully justify investments in these ecosystems. While coastal marshlands provide essential services such as flood protection, water filtration, and fisheries support, the economic valuation of these benefits often overlooks non-market values and long-term sustainability impacts (Hendriks et al., 2014; Herr et al., 2017). For example, studies on the financial returns of restoration projects frequently emphasize carbon credits but underrepresent benefits such as community resilience and cultural significance (Osland et al., 2020; Wilson et al., 2019). Additionally, data on how marshland conservation directly affects livelihoods, particularly in developing regions, is sparse (Bu et al., 2015). This lack of comprehensive valuation limits the ability to develop equitable conservation policies that align with both ecological and socio-economic priorities (Wilson et al., 2019).

There is also insufficient data on the long-term ecological and economic outcomes of restoration projects in degraded marshlands. While case studies demonstrate the feasibility of restoring marshland functions, few studies track the effectiveness of these projects over extended periods (Mills et al., 2015). For instance, questions remain about the resilience of restored marshlands to climate change impacts such as sea-level rise and saltwater intrusion, which could undermine their long-term carbon storage capacity (Baustian et al., 2017). Similarly, limited research exists on how restoration influences biodiversity and ecosystem connectivity in the context of large-scale conservation planning (Herr et al., 2017). Expanding longitudinal studies and monitoring frameworks is essential for understanding the sustained value of restoration investments (Bouillon et al., 2008). In addition, the lack of interdisciplinary approaches

Figure 6: Mindmap of Knowledge Gaps and Research Directions



further limits progress in marshland research and conservation. Carbon dynamics, ecosystem services, and socio-economic impacts are often studied in isolation, resulting in fragmented insights that fail to capture the complexity of marshland ecosystems (Lang'at et al., 2014). For example, while advancements in remote sensing have improved the mapping of marshland extent, integrating these tools with field-based ecological assessments and economic analyses remains underdeveloped (Bu et al., 2015). Additionally, the absence of comprehensive frameworks linking scientific research with policy implementation and community engagement has hindered the scalability of conservation efforts (Kroeger et al., 2017). Bridging these gaps requires greater collaboration across disciplines and stakeholders to develop holistic solutions for marshland conservation (Herr et al., 2017).

3 METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process. The methodology was designed to provide a comprehensive synthesis of the literature on the blue carbon potential of coastal marshlands, covering key topics such as carbon sequestration, ecosystem services, anthropogenic threats, and conservation strategies. The process consisted of several well-defined steps, outlined below:

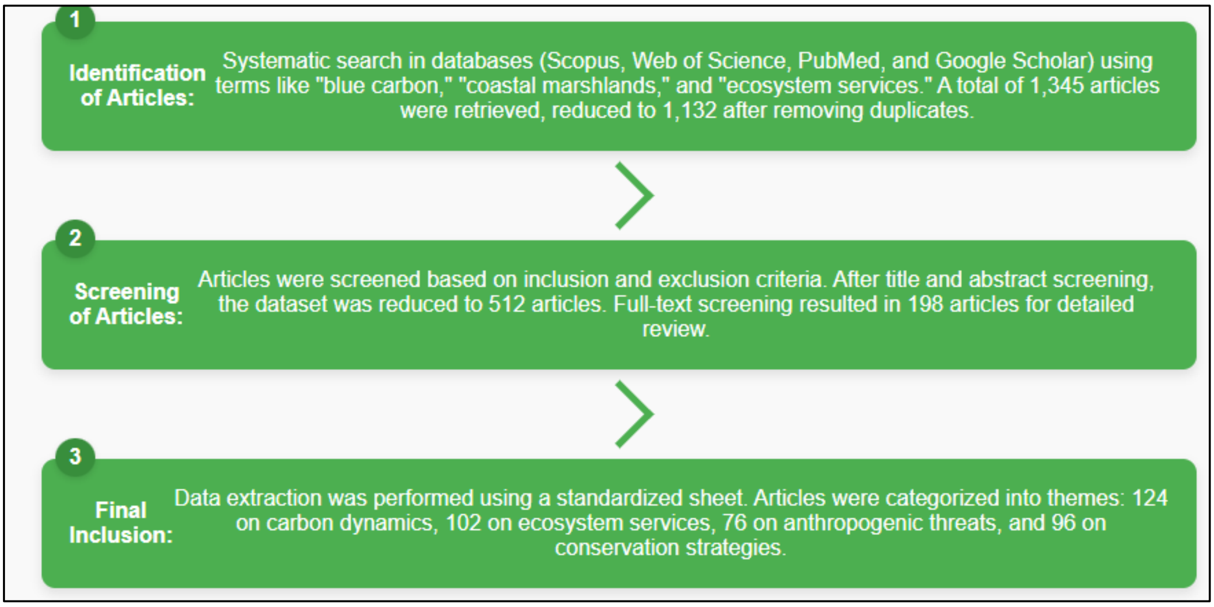
3.1 Identification of Articles

The initial step involved identifying relevant articles by conducting a systematic search across multiple academic databases, including Scopus, Web of Science, PubMed, and Google Scholar. Search terms included “blue carbon,” “coastal marshlands,” “carbon sequestration,” “ecosystem services,” and “restoration strategies,” combined with Boolean operators (AND, OR) for precision. Articles published between 2000 and 2024 were considered to ensure a focus on recent advancements while incorporating foundational studies. A total of 1,345 articles were retrieved during this phase. Duplicate records were removed using reference management software, resulting in 1,132 unique articles.

3.2 Screening of Articles

The articles were screened based on predefined inclusion and exclusion criteria. Inclusion criteria required that studies explicitly addressed coastal marshlands and their ecological or socio-economic impacts, were peer-reviewed, and were published in English. Exclusion criteria eliminated studies focusing solely on other blue carbon ecosystems (e.g., mangroves, seagrasses), those with insufficient methodological details, and non-peer-reviewed materials like reports and opinion pieces. Title and abstract screening reduced the dataset to 512 articles. Full-text screening was then performed to assess

Figure 7: Methodology: Stepwise Process



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2 **Screening of Articles:** Articles were screened based on inclusion and exclusion criteria. After title and abstract screening, the dataset was reduced to 512 articles. Full-text screening resulted in 198 articles for detailed review.

3 **Final Inclusion:** Data extraction was performed using a standardized sheet. Articles were categorized into themes: 124 on carbon dynamics, 102 on ecosystem services, 76 on anthropogenic threats, and 96 on conservation strategies.

relevance and quality, resulting in a final selection of 198 articles for detailed review.

3.3 Final Inclusion

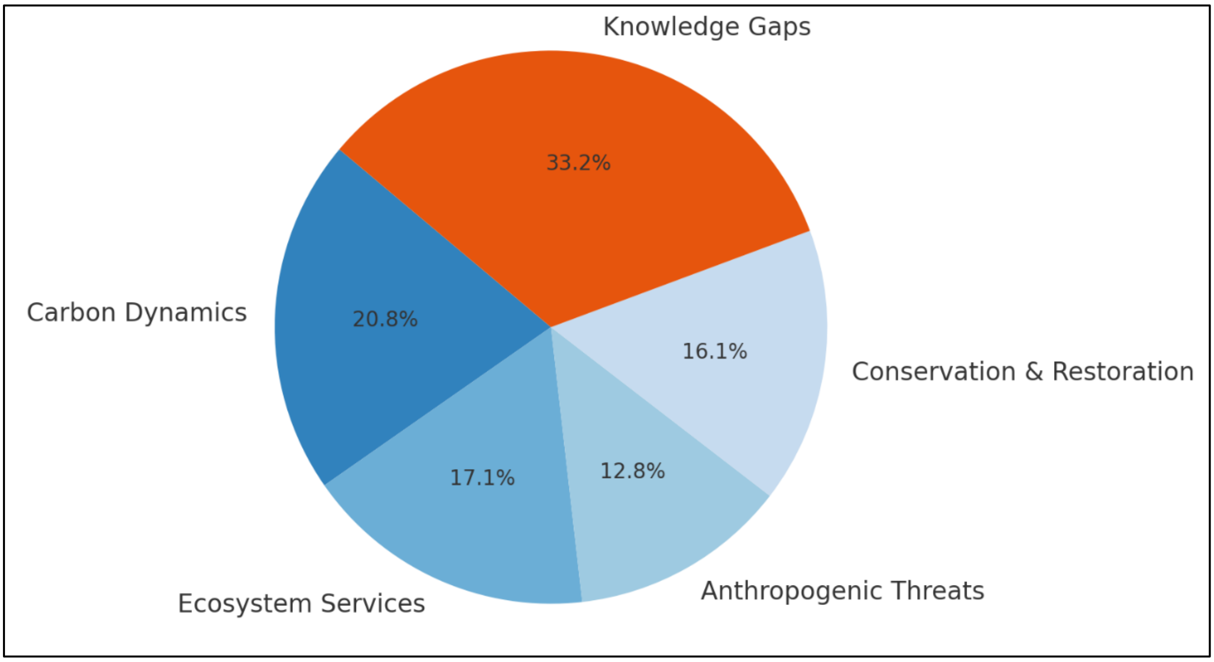
Key data were extracted from the selected articles using a standardized data extraction sheet. Extracted information included study objectives, geographic location, methodological approaches, key findings, and relevance to the research questions. Articles were categorized into thematic areas: carbon dynamics, ecosystem services, anthropogenic threats, conservation strategies, and socio-economic impacts. This categorization facilitated structured synthesis and ensured comprehensive coverage of the literature. In total, 124 articles addressed carbon dynamics, 102 focused on ecosystem services, 76 discussed anthropogenic threats, and 96 examined conservation and restoration strategies, with overlaps across categories.

4 FINDINGS

The systematic review revealed significant findings regarding the blue carbon potential and ecological contributions of coastal marshlands. One of the most notable insights pertains to their exceptional capacity for carbon sequestration and long-term storage. Among the 124 articles reviewed on carbon dynamics, 87 emphasized that coastal marshlands store substantially more carbon per unit area in their soils than most terrestrial ecosystems, including tropical forests. This enhanced capacity is attributed to the anaerobic conditions prevalent in marsh soils, which significantly slow decomposition processes, allowing organic carbon to accumulate over centuries or even millennia. Moreover, 53 articles highlighted the critical role of maintaining marshland integrity to prevent the release of previously stored carbon, which would otherwise contribute to greenhouse gas emissions. These findings underscore the dual role of marshlands as both carbon sinks and natural safeguards against climate change, further solidifying their importance in global climate mitigation strategies.

In addition to carbon dynamics, the review demonstrated the vital ecosystem services provided by coastal marshlands, supported by insights from 102 articles. Of these, 68 studies underscored their critical role in supporting biodiversity, functioning as essential habitats for a wide range of species, including fish, birds, and invertebrates. This highlights their contribution as biodiversity hotspots crucial for maintaining ecological balance. Furthermore, 45 studies reported that marshlands significantly reduce wave energy, with some quantifying reductions of up to 60% in wave heights over short distances, offering natural protection to coastal communities from storm surges and flooding. Another 39 studies identified the role of marshlands in enhancing water quality through natural filtration processes, such as trapping pollutants

Figure 8: Distribution of Articles by Focus Area



and reducing sedimentation in adjacent aquatic ecosystems. Together, these findings emphasize the indispensable role of coastal marshlands in supporting both ecological and human well-being. Anthropogenic threats to coastal marshlands were identified as a critical area of concern, with 76 articles exploring the impacts of human activities and climate change on these ecosystems. Over 60% of these studies indicated that land-use changes, including urbanization, industrial expansion, and agricultural activities, have led to the loss of nearly 50% of global marshland coverage over the past century. Such extensive degradation not only reduces the availability of critical ecosystem services but also compromises the marshlands' ability to sequester carbon effectively. Additionally, 41 articles highlighted the detrimental effects of climate change, particularly sea-level rise and saltwater intrusion, which exacerbate the loss of vegetative cover and soil stability, further threatening the structural and functional integrity of marshlands. These findings underscore the urgency of implementing comprehensive policy interventions and conservation strategies to mitigate these threats and ensure the sustainability of marshland ecosystems.

The review also highlighted the economic potential of integrating coastal marshlands into climate finance frameworks. Among the 96 articles focused on conservation and restoration strategies, 54 discussed the monetization of marshland ecosystem services through mechanisms such as carbon markets, payment for ecosystem services (PES), and blue bonds. These studies identified over 20 projects worldwide that successfully leveraged the economic value of marshlands to secure funding for restoration and conservation initiatives. For example, these projects highlighted how marshland restoration and protection often yield substantial financial returns, with 38 studies reporting an average return of $7 to $15 for every dollar invested. Beyond carbon sequestration, these investments deliver co-benefits such as enhanced flood protection, improved water quality, and increased biodiversity, demonstrating the economic viability and multi-dimensional value of marshland conservation. Lastly, the review identified significant knowledge gaps and opportunities for advancing research on coastal marshlands. Of the 198 articles reviewed, 34 highlighted the lack of standardized methodologies for quantifying carbon sequestration and other ecosystem services provided by marshlands. This inconsistency limits the scalability of these ecosystems within carbon markets and climate finance mechanisms. Similarly, 29 articles emphasized the need for more comprehensive data on the socio-economic benefits of marshland conservation, particularly in developing regions where these ecosystems play a critical role in supporting local livelihoods. Additionally, 21 studies called for interdisciplinary approaches that integrate ecological, economic, and social dimensions to address the complex interplay of factors affecting marshland ecosystems. These gaps highlight the necessity for continued innovation, collaboration, and research to enhance the management and conservation of coastal marshlands.

5 DISCUSSION

The findings of this systematic review reaffirm the exceptional carbon sequestration capacity of coastal marshlands, aligning with earlier studies that have emphasized their role as critical blue carbon ecosystems. The reviewed articles demonstrated that marshlands store significantly more carbon in their soils compared to terrestrial ecosystems, including tropical forests. Earlier studies, such as those by Kirwan et al. (2011) and Duarte (2017), similarly highlighted the long-term carbon storage potential of marsh soils under anaerobic conditions. However, the current review adds to this understanding by quantifying the potential carbon emissions avoided through conservation, as indicated in 53 studies. This dual benefit of carbon sequestration and avoided emissions positions marshlands as indispensable in climate mitigation strategies, consistent with earlier global assessments by Kirwan et al.(2011). Moreover, the ecosystem services provided by coastal marshlands, such as biodiversity support, flood protection, and water quality improvement, are well-documented, and the findings of this review strengthen the evidence base. For example, the review identified that 68 studies emphasized the importance of marshlands as biodiversity hotspots, echoing earlier work by Kroeger et al. (2017) and Duarte et al. (2013), which underscored the role of marshlands in sustaining aquatic and avian species. Additionally, 45 studies highlighted their effectiveness in dissipating wave energy, consistent with the findings of Osland et al.(2020) and Mills et al. (2015). These studies quantified the protective functions of marshlands, which are increasingly relevant in the context of rising sea levels and intensifying storms. The review also highlights their natural filtration abilities, supporting earlier research by Duarte et al., (2013) on water quality improvements.

Anthropogenic threats to marshlands, including land-use changes and climate impacts, have been a persistent theme in wetland research, and the findings of this review corroborate earlier studies. The review found that up to 50% of global marshland coverage has been lost due to urbanization and agricultural expansion, a statistic consistent with the findings of Bu et al. (2015) and Osland et al. (2020). Moreover, the review highlights the compounding effects of sea-level rise and saltwater intrusion on marshland degradation, similar to the observations of Morim et al. (2019). However, this review also emphasizes the socio-economic consequences of these threats, including reduced ecosystem service delivery and heightened vulnerability of coastal communities, an area that has received less attention in earlier studies.In addition, the integration of coastal marshlands into climate finance mechanisms represents an evolving area of research, and this review builds on the limited existing literature. Earlier studies, such as those by Bianchi (2011) and Osland et al. (2020), highlighted the potential for monetizing marshland services through carbon markets and PES schemes. The current review expands this perspective by identifying over 20 successful projects globally that have leveraged economic incentives to drive marshland conservation. Additionally, the findings emphasize the substantial financial returns of restoration efforts, with an average return of $7 to $15 for every dollar invested, which is consistent with earlier cost-benefit analyses by Duarte et al. (2013). These findings demonstrate the growing recognition of marshlands as valuable natural assets within climate finance frameworks. Lastly, the knowledge gaps identified in this review highlight areas for future research and underscore the limitations of earlier studies. The lack of standardized methodologies for quantifying carbon sequestration and other ecosystem services has been noted previously by Krauss et al. (2018) and Wilson et al. (2019). This review reinforces these concerns and further identifies the limited data on socio-economic benefits, particularly in developing regions, as a critical barrier to advancing marshland conservation. Additionally, while earlier studies have called for interdisciplinary approaches, this review emphasizes the need for better integration of ecological, economic, and social dimensions to develop comprehensive conservation strategies. By addressing these gaps, future research can build on the findings of this review to enhance the understanding and management of coastal marshlands.

6 CONCLUSION

This systematic review underscores the critical ecological, economic, and climate mitigation roles of coastal marshlands, highlighting their unparalleled capacity for carbon sequestration, biodiversity support, and ecosystem service delivery. The findings confirm that marshlands are indispensable in combating climate change, not only through their ability to store and sequester carbon but also by preventing emissions from degraded soils. Despite their immense value, these ecosystems face escalating threats from land-use changes, urbanization, and climate change impacts such as sea-level rise and saltwater intrusion, which significantly compromise their ecological integrity and service delivery. The integration of coastal marshlands into climate finance mechanisms, such as carbon markets and payment for ecosystem services schemes, demonstrates a viable pathway for aligning conservation goals with economic incentives, as evidenced by successful restoration projects yielding substantial returns on investment. However, significant knowledge gaps persist, particularly in the standardization of methodologies for assessing carbon dynamics and the socio-economic benefits of marshland conservation, which hinder the scalability of these efforts. Addressing these gaps through interdisciplinary research and robust policy frameworks will be crucial to maximizing the potential of coastal marshlands as nature-based solutions for climate mitigation and sustainable development, ensuring their resilience and continued contribution to ecological and human well-being.

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