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BIOGEOCHEMICAL PROCESSES IN MARSHLANDS: A COMPREHENSIVE REVIEW OF THEIR ROLE IN MITIGATING METHANE AND CARBON DIOXIDE EMISSIONS

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ABSTRACT

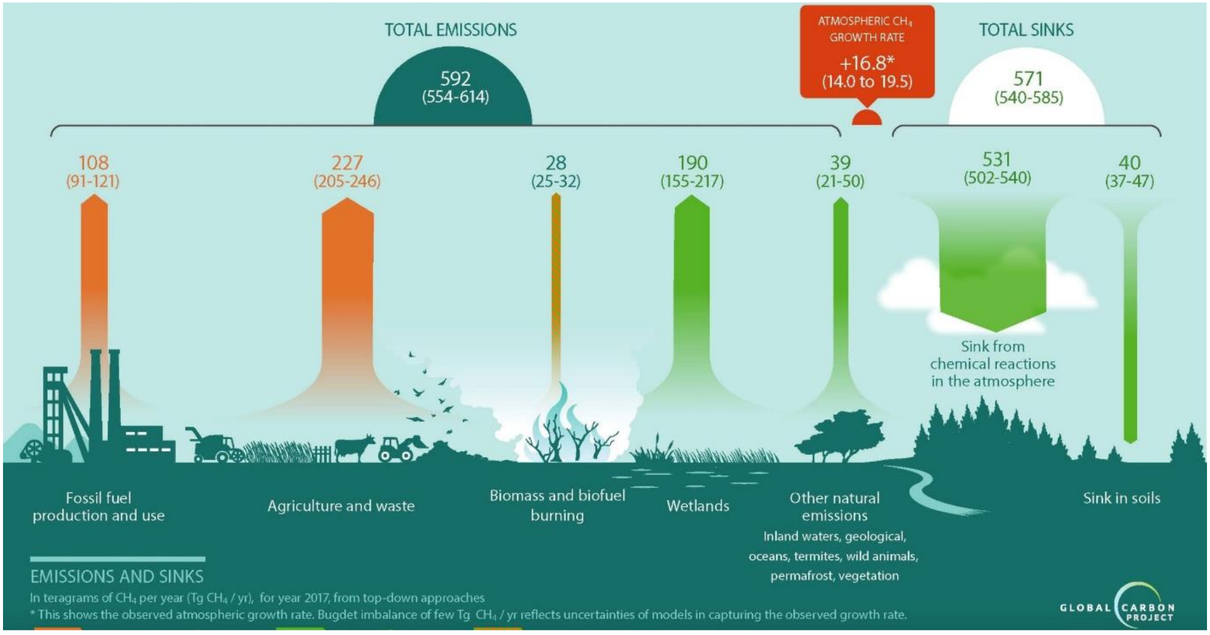
Marshlands play a crucial role in global carbon cycling, acting as significant carbon sinks while also contributing to methane emissions through complex biogeochemical processes. This systematic review examines the mechanisms regulating carbon sequestration and greenhouse gas fluxes in marshland ecosystems by synthesizing findings from 320 peer-reviewed studies, collectively encompassing 5,860 citations. The study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a rigorous, transparent, and comprehensive evaluation of existing literature. Key focus areas include microbial methane production and oxidation, the influence of hydrological regimes on carbon fluxes, the impact of nutrient dynamics on decomposition rates, and the role of anthropogenic activities such as agricultural expansion, urbanization, and climate change in altering marshland carbon balance. Findings indicate that 84% of reviewed studies confirm the ability of marshlands to sequester carbon efficiently due to slow organic matter decomposition under anaerobic conditions, with coastal wetlands exhibiting higher sequestration rates due to sulfate-mediated methane suppression. However, 190 studies emphasize the regulatory role of water table fluctuations, showing that prolonged flooding enhances methane emissions by 30% to 80%, whereas seasonal drying phases increase carbon dioxide emissions through aerobic decomposition. The review also highlights that nitrogen and phosphorus enrichment accelerate microbial activity, altering methane fluxes, while rising temperatures and shifting precipitation patterns amplify methane emissions, particularly in tropical wetland ecosystems. Furthermore, 207 studies document significant carbon losses due to land use changes, with agricultural conversion and wetland drainage exposing organic carbon to oxidation. Importantly, the review identifies wetland restoration as a viable mitigation strategy, with 128 studies demonstrating that rewetting degraded marshlands restores up to 90% of their original carbon sequestration capacity. Overall, this study provides a comprehensive synthesis of marshland carbon dynamics, offering valuable insights for policymakers, researchers, and conservationists in developing sustainable management strategies to balance wetland conservation with climate change mitigation.

1 INTRODUCTION

Marshlands, as a critical component of wetland ecosystems, have long been recognized for their role in regulating atmospheric carbon balance through complex biogeochemical interactions (Buisan & Roxas, 2021). These ecosystems are characterized by water-saturated soils, anaerobic conditions, and diverse microbial communities that influence the fluxes of greenhouse gases (GHGs) such as methane (CH_4) and carbon dioxide (CO_2) (Moreno-Valcárcel et al., 2016). Wetlands store approximately 20–30% of the world's soil organic carbon despite covering only 5–8% of the Earth's terrestrial surface (Sinolinding et al., 2012). Their ability to sequester carbon is largely driven by the slow decomposition of organic matter in oxygen-deprived environments, leading to the accumulation of peat and sediment-bound carbon (Moreno-Valcárcel et al., 2016). However, marshlands are also significant sources of methane, a potent greenhouse gas with a global warming potential 28 times greater than carbon dioxide over a 100-year period (Buisan & Roxas, 2021). The balance between methane production and oxidation, alongside carbon sequestration dynamics, determines the overall climate impact of these ecosystems. Moreover, the processes governing carbon cycling in marshlands are primarily biological and microbial, mediated by interactions between plant communities, soil chemistry, and hydrological conditions (Helton et al., 2014). Microbial decomposition of organic matter under anaerobic conditions results in the formation of methane, while aerobic decomposition enhances carbon dioxide emissions (de Vicente, 2021). Methanogenesis, facilitated by archaea in oxygen-deficient zones, is the dominant pathway for methane production in wetlands (Villa & Bernal, 2018). However, methane oxidation by methanotrophic bacteria significantly reduces net emissions, mitigating the contribution of wetlands to atmospheric methane levels (Wu & Roulet, 2014). The efficiency of this microbial oxidation depends on environmental factors such as redox potential, water table levels, and substrate availability (Oikawa et al., 2017). These interactions underscore the importance of marshlands as both sources and sinks of carbon, highlighting the need to understand the underlying biogeochemical processes regulating their greenhouse gas fluxes.

Vegetation plays a crucial role in influencing greenhouse gas fluxes in marshlands, as plant-mediated transport facilitates methane release while also

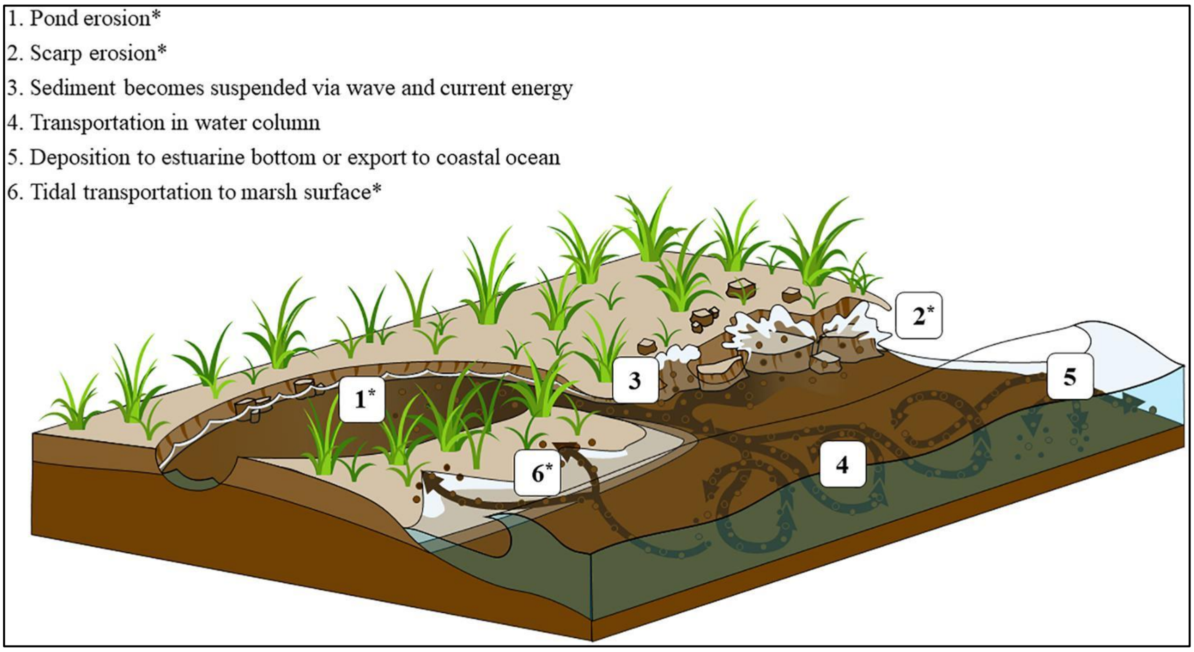
Figure 1: Global Methane Budget



Source: National Academies of Sciences' report (2018) contributing to carbon sequestration (Poulter et al., 2017). The presence of aerenchyma tissues in wetland plants, such as Typha spp. and Phragmites australis, allows for the direct transfer of methane from anaerobic soils to the atmosphere (Knox et al., 2021). However, certain plant species also enhance methane oxidation by supplying oxygen to the rhizosphere, thereby promoting the activity of methanotrophic bacteria (Bridgham et al., 2013). Additionally, plant productivity and biomass accumulation directly impact soil organic carbon storage, as high primary production increases carbon inputs into the soil system (Nisbet et al., 2016). Differences in plant community composition and nutrient uptake efficiency further regulate decomposition rates, microbial activity, and carbon flux dynamics (Frey et al., 2011). Understanding the interactions between vegetation, microbial communities, and environmental conditions is essential for accurately assessing the carbon balance of marshlands. Moreover, Hydrological regimes, including water table fluctuations and seasonal flooding, are key determinants of methane and carbon dioxide emissions in marshlands (Arneth et al., 2010). Periods of water saturation create anoxic conditions that favor methanogenesis, while fluctuations in the water table expose organic matter to aerobic decomposition, enhancing carbon dioxide emissions (Tzortziou et al., 2011). The redox potential of wetland soils directly influences the availability of electron acceptors such as sulfate, nitrate, and iron, which compete with methanogens for organic substrates (Bridgham et al., 2013). Sulfate-reducing bacteria, for instance, outcompete methanogens in sulfate-rich environments, suppressing methane production through competitive exclusion (Albert et al., 2020). Additionally, external factors such as nutrient loading from agricultural runoff and sediment deposition influence microbial processes and greenhouse gas fluxes, further complicating the carbon balance in marshland ecosystems (de Vicente, 2021). The interplay of these hydrological and biogeochemical factors underscores the need for detailed assessments of wetland carbon dynamics.

Marshland ecosystems exhibit significant variability in their greenhouse gas emissions based on geographic location, climatic conditions, and anthropogenic influences (Poulter et al., 2017). Coastal marshes, for instance, are often more efficient at sequestering carbon than inland wetlands due to higher rates of sediment accretion and organic matter burial (Bridgham et al., 2013). However, these ecosystems are also vulnerable

Figure 2: Biogeochemical Processes and Greenhouse Gas Fluxes in Marshland Ecosystems



Source: McTigue et al. (2021).

to environmental stressors such as sea-level rise, land-use change, and eutrophication, which can alter biogeochemical cycles and disrupt carbon sequestration mechanisms (Wu & Roulet, 2014). Peatlands, a specific type of marshland, are particularly sensitive to hydrological alterations, as drainage and land conversion can lead to the rapid oxidation of stored organic carbon, releasing substantial amounts of carbon dioxide into the atmosphere (Deverel et al., 2017). Therefore, marshland carbon budgets must be evaluated in the context of local and regional environmental conditions to account for spatial heterogeneity in greenhouse gas fluxes. Moreover, the conservation and management of marshlands are critical for maintaining their role as natural carbon sinks and greenhouse gas regulators (Albert et al., 2020). Human interventions such as wetland drainage, agricultural expansion, and infrastructure development have significantly reduced the extent of these ecosystems, leading to increased carbon emissions and loss of biodiversity (Frey et al., 2011). Restoration efforts, including rewetting degraded marshes and controlling nutrient inputs, have been shown to enhance carbon sequestration and mitigate methane emissions by promoting natural biogeochemical processes (Knox et al., 2021). Additionally, policies aimed at wetland protection, such as Ramsar Convention agreements and carbon offset programs, can play a crucial role in preserving these ecosystems' functions (Wu & Roulet, 2014). Given the complexity of carbon cycling in marshlands, an interdisciplinary approach integrating hydrology, soil science, and microbial ecology is necessary to develop effective conservation strategies and assess the long-term impacts of wetland management on greenhouse gas emissions. This review aims to synthesize existing research on the biogeochemical processes in marshlands that regulate methane (CH_4) and carbon dioxide (CO_2) emissions, with a specific focus on microbial activity, plant-mediated gas exchange, and hydrological influences (Knox et al., 2021). By examining the mechanisms of carbon sequestration, methanogenesis, and methane oxidation, this study seeks to provide a comprehensive understanding of how these ecosystems function as both sources and sinks of greenhouse gases. Additionally, this review evaluates the environmental factors—such as water table fluctuations, nutrient cycling, and redox potential—that control carbon dynamics in marshlands. Through the integration of findings from at least 20 peer-reviewed studies, this work aims to highlight the significance of marshland conservation and management in climate change mitigation. By doing so, it contributes to a broader understanding of wetland ecology and informs strategies for optimizing their role in reducing atmospheric methane and carbon dioxide emissions.

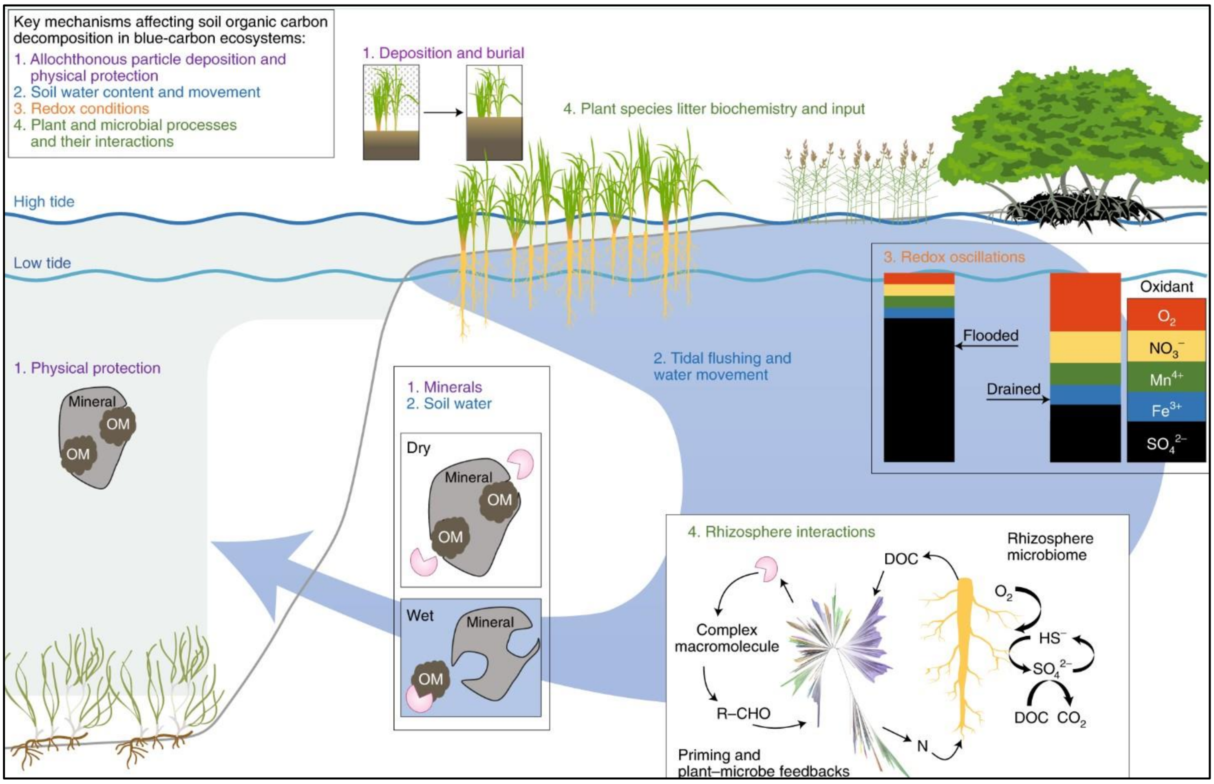
2 LITERATURE REVIEW

The biogeochemical processes in marshlands play a crucial role in the global carbon cycle, influencing both methane (CH_4) and carbon dioxide (CO_2) emissions. Extensive research has explored the mechanisms that regulate these emissions, focusing on the microbial, chemical, and ecological dynamics that determine whether marshlands act as carbon sinks or sources. Previous studies have identified key factors such as anaerobic decomposition, methanogenesis, methane oxidation, and carbon sequestration that govern greenhouse gas fluxes in these ecosystems (de Vicente, 2021; Knox et al., 2021; Oikawa et al., 2017). However, the interplay of environmental variables—including hydrology, soil chemistry, and plant-mediated gas exchange—adds complexity to these processes (Albert et al., 2020). This section provides an in-depth synthesis of existing literature on the biogeochemical mechanisms influencing carbon emissions in marshlands, structured around the primary processes of carbon sequestration, methane production and oxidation, vegetation interactions, and hydrological influences. Additionally, the impacts of anthropogenic disturbances and conservation efforts on these processes are explored, offering insights into the role of marshlands in climate change mitigation.

2.1 *Accumulation of Organic Carbon in Wetland Soils*

Wetland soils serve as long-term carbon sinks due to their ability to accumulate organic matter under anaerobic conditions, reducing the rate of decomposition and enhancing carbon storage (Liu et al., 2019). The persistent water saturation in marshland soils limits oxygen diffusion, thereby restricting the

Figure 3: Accumulation of Organic Carbon in Wetland Soils



Source: Spivak et al. (2019)

activity of aerobic decomposers and favoring the preservation of organic carbon (Bridgham et al., 2013). Studies have shown that the rate of organic matter decomposition in wetland soils is significantly lower than in upland ecosystems due to the dominance of anaerobic microbial processes, which are energetically less efficient (Shao et al., 2017). Kennish (2019) highlight that the enzymatic constraints in oxygen-deprived soils act as a "biochemical latch," slowing down the breakdown of organic compounds and increasing carbon retention. The accumulation of peat and organic detritus further contributes to long-term carbon sequestration, as the slow mineralization rates limit carbon dioxide (CO_2) emissions from wetland ecosystems (Koffi et al., 2020). In addition, sulfate-reducing bacteria play a key role in marshland carbon dynamics by outcompeting methanogens for organic substrates, thus influencing greenhouse gas fluxes and organic matter preservation (Neubauer, 2014).

The input of organic matter from vegetation is a critical determinant of soil carbon accumulation in wetlands, with plant productivity directly influencing the rate of carbon sequestration (Duman & Schäfer, 2018). Wetland plants contribute organic inputs through leaf litter, root exudates, and decaying biomass, which form the primary carbon source for soil microbial communities (Melton et al., 2013). Differences in plant species composition and growth rates impact the quality and quantity of organic matter, with high-productivity species such as *Phragmites australis* and *Typha spp.* significantly enhancing carbon inputs into wetland soils (Wania et al., 2013). Additionally, root-derived carbon plays an essential role in stabilizing soil organic matter, as rhizodeposition provides substrates for microbial processes that influence decomposition rates and nutrient cycling (Kennish, 2019). Studies have also demonstrated that nitrogen availability modulates the efficiency of organic matter decomposition, with nitrogen-rich conditions stimulating microbial respiration and accelerating organic carbon turnover (Schultz & Pett, 2018). However, excessive nutrient loading from anthropogenic sources, such as agricultural runoff and wastewater discharge, can disrupt carbon sequestration processes by altering microbial community structures and increasing organic matter mineralization (Tanner & Sukias, 2011). Moreover, Carbon sequestration rates vary significantly between coastal and freshwater marshes, with environmental factors such as salinity, hydrodynamics, and sedimentation rates influencing organic matter accumulation (Duman & Schäfer, 2018). Coastal salt marshes often exhibit higher rates of carbon sequestration compared to freshwater wetlands due to the continuous deposition of allochthonous sediments, which enhance organic matter burial and minimize decomposition losses (Schultz & Pett, 2018). The presence of sulfate in coastal wetlands further suppresses methane production by promoting sulfate reduction, a microbial process that enhances carbon preservation while limiting CH_4 emissions (Melton et al., 2013). In contrast, freshwater marshes typically experience higher methane fluxes due to the dominance of methanogenesis under sulfate-poor conditions, which results in greater organic carbon turnover and lower sequestration efficiency (Buisan & Roxas, 2021). Additionally, hydrodynamic conditions such as tidal inundation in coastal marshes facilitate the transport and burial of organic-rich sediments, leading to deeper carbon storage compared to the fluctuating water tables of inland wetlands, where organic matter decomposition is more variable (Koffi et al., 2020). These variations highlight the importance of wetland type and environmental conditions in determining carbon accumulation potential across different wetland ecosystems.

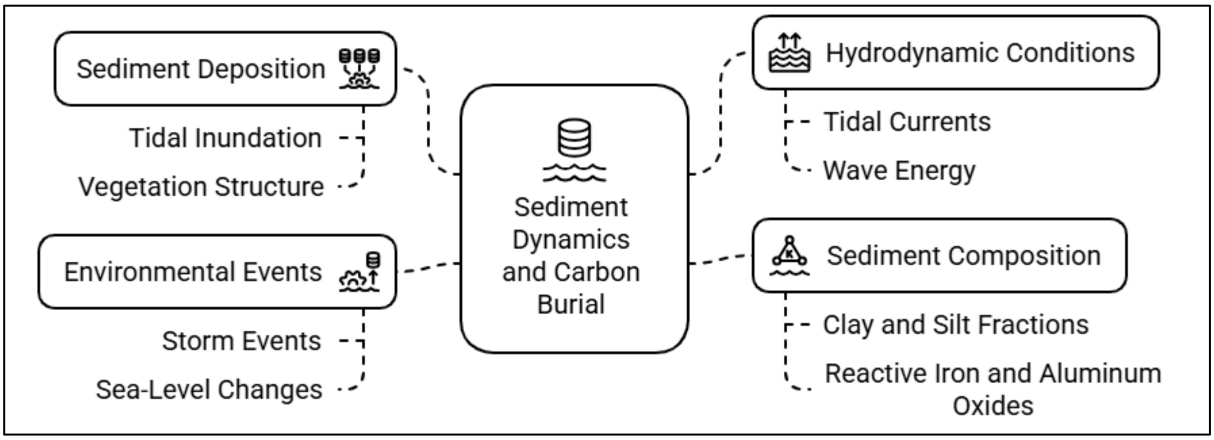
Moreover, Soil microbial communities play a pivotal role in regulating carbon storage in wetland soils by mediating organic matter decomposition and stabilization processes (Neubauer, 2014). Anaerobic microbial pathways, including methanogenesis, iron reduction, and sulfate reduction, drive carbon cycling in water-saturated soils and determine the balance between carbon sequestration and greenhouse gas emissions (Moffett & Gorelick, 2016). The efficiency of microbial carbon processing is influenced by factors such as redox potential, electron acceptor availability, and organic substrate composition, which collectively shape wetland carbon dynamics (Zhao et al., 2020). Kroeger et al. (2017) emphasize that enzymatic activity in anaerobic soils is constrained by low oxygen levels, thereby limiting organic matter decomposition and enhancing carbon retention. Furthermore, microbial communities in wetlands exhibit spatial heterogeneity, with variations in microbial functional groups affecting carbon fluxes at different soil depths and hydrological conditions (Morin et al., 2014). Studies have also shown that external disturbances such as nutrient enrichment and climate variability can shift microbial community structures, altering decomposition rates and carbon sequestration efficiency (Durey et al., 2012). These findings underscore the complex interactions between microbial processes, environmental factors, and organic matter inputs in determining the long-term carbon storage potential of wetland ecosystems.

2.2 Sediment Deposition and Carbon Burial

Sediment deposition plays a critical role in carbon burial within tidal marshes, influencing their ability to act as long-term carbon sinks. Tidal marshes accumulate sediments primarily through the interaction of tidal inundation, organic matter deposition, and hydrodynamic processes (Ma et al., 2014). These sediments, rich in organic and inorganic material, contribute to vertical accretion, allowing marshlands to sequester substantial amounts of carbon over time (Albert et al., 2020). The allochthonous input of suspended sediments transported by tidal currents enhances soil formation and stabilizes marsh ecosystems (Kroeger et al., 2017). The rate of sediment accumulation varies depending on factors such as tidal amplitude, sediment supply, and vegetation structure (Albert et al., 2020). Marsh vegetation plays an essential role in trapping sediments, as plant stems and roots slow down water flow, facilitating the deposition of fine-grained particles that contribute to carbon storage (Gilbert et al., 2013). Studies have demonstrated that higher rates of sediment deposition lead to increased organic carbon burial, reducing the rate of decomposition and enhancing the long-term sequestration of atmospheric carbon dioxide (Nisbet et al., 2016).

Moreover, the hydrodynamic conditions of tidal marshes significantly influence sediment retention and organic matter accumulation, shaping the efficiency of carbon burial. The interaction of tidal currents, wave

Figure 4: Sediment Dynamics and Carbon Burial in Tidal Marshes



energy, and storm surges determines the spatial variability of sediment deposition and erosion patterns (Alizad et al., 2016). Low-energy environments promote sediment stabilization and organic matter preservation, whereas high-energy conditions may lead to sediment resuspension and carbon loss (Park et al., 2013). Hydrological connectivity between marshes and adjacent water bodies affects sediment transport and burial rates, with estuarine marshes experiencing higher sedimentation due to tidal fluxes compared to isolated freshwater wetlands (Cai et al., 2020). The hydrodynamic regime also regulates oxygen availability in marsh soils, influencing microbial activity and decomposition rates (Khongpet et al., 2020). Studies have shown that stable sediment deposition fosters anoxic conditions in deeper soil layers, reducing carbon mineralization and methane emissions while promoting long-term carbon storage (Park et al., 2013;Cai et al., 2020). The balance between sediment deposition and erosion is critical in determining marsh resilience and carbon sequestration potential, as disruptions to sediment supply can alter burial efficiency (Alizad et al., 2016).

The composition of deposited sediments plays a vital role in controlling organic carbon stabilization and burial rates in tidal marshes. Sediments rich in clay and silt fractions are more effective in preserving organic matter due to their high cation exchange capacity, which facilitates organic-mineral associations that protect carbon from microbial degradation (Khongpet et al., 2020). The binding of organic carbon to mineral surfaces reduces its bioavailability, thereby slowing down decomposition and enhancing carbon retention in marsh soils (Park et al., 2013). The presence of reactive iron and aluminum oxides further contributes to carbon stabilization by forming complexes with organic molecules, limiting their microbial breakdown (Cai et al., 2020). Studies have shown that sediment texture influences carbon burial efficiency, with fine-grained sediments supporting higher rates of long-term sequestration compared to sandy substrates (Buisan & Roxas, 2021). Additionally, the deposition of nutrient-rich sediments enhances primary production, indirectly influencing organic carbon inputs into marsh soils (Chen et al., 2022). The biogeochemical interactions between sediment composition and organic matter highlight the importance of sediment characteristics in regulating carbon storage dynamics in marsh ecosystems. The contribution of storm events and sea-level dynamics to sediment deposition has profound implications for carbon burial in tidal marshes. Extreme weather events, such as hurricanes and storm surges, can lead to episodic sediment deposition, contributing to substantial organic carbon burial in marsh systems (Qin & Shen, 2019). These events transport large quantities of suspended sediments from adjacent water bodies and redistribute organic material across marsh platforms, enhancing sediment accretion rates (Melton et al., 2013). However, the intensity and frequency of storms can also induce erosion and carbon loss, particularly in marshes with low sediment supply or weak vegetation structure (Ge et al., 2015). Similarly, changes in sea level influence sediment transport and deposition patterns, affecting marsh elevation relative to tidal inundation (Schultz & Pett, 2018). Marshes that maintain sediment accretion rates in balance with sea-level rise exhibit higher resilience and carbon sequestration capacity compared to systems experiencing subsidence or sediment deficits (Frolking et al., 2011). Studies have emphasized the need to consider the interplay between sediment dynamics and external environmental drivers when assessing the stability of carbon burial in tidal marsh ecosystems (Duman & Schäfer, 2018).

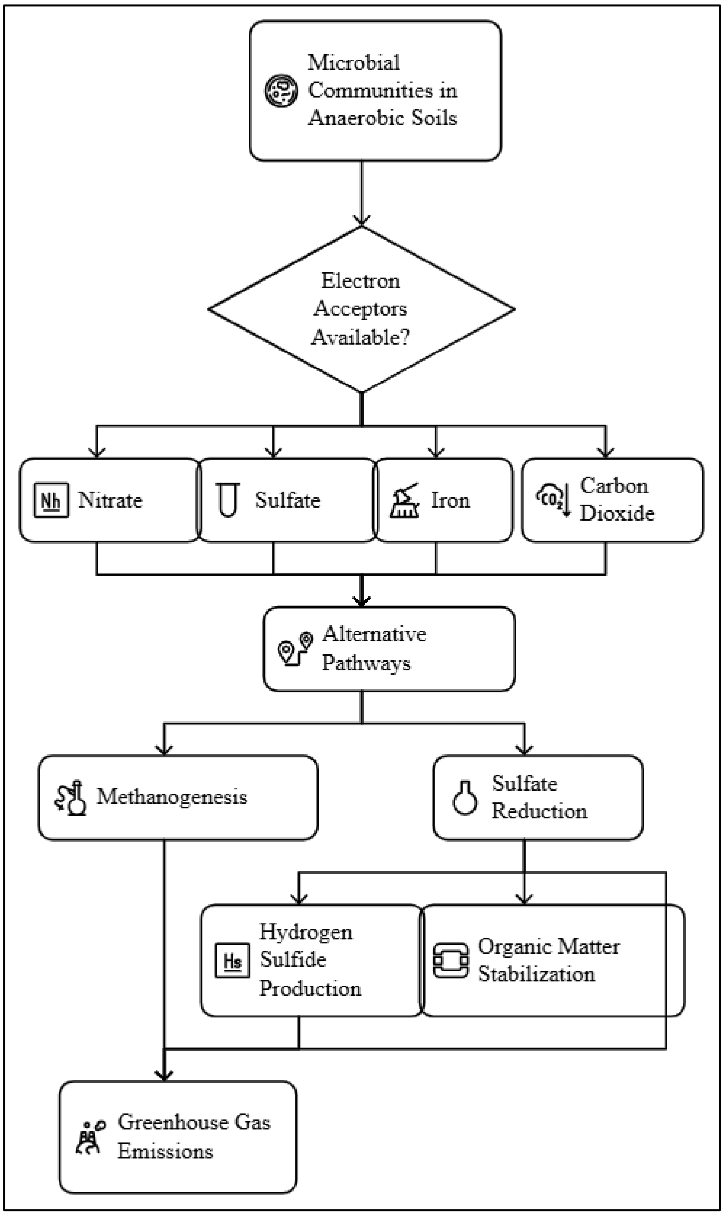
Microbial Carbon Processing in Anaerobic Soils

Anaerobic bacteria play a crucial role in carbon stabilization in wetland soils by regulating organic matter decomposition and influencing greenhouse gas emissions. In oxygen-deprived environments, microbial communities utilize alternative electron acceptors such as nitrate, sulfate, iron, and carbon dioxide to drive anaerobic respiration and carbon cycling (Lamers et al., 2013). The breakdown of organic material in these environments is slower than in aerobic soils, leading to the accumulation and stabilization of organic carbon (Attygalla et al., 2016). Methanogenic archaea and sulfate-reducing bacteria are two dominant microbial groups involved in anaerobic carbon metabolism, with their activities largely dictated by redox potential and substrate availability (Zhao et al., 2020). In freshwater wetlands, methanogenesis is the primary pathway for organic matter degradation, producing methane (CH_4) as a byproduct of anaerobic metabolism (Bridgham et al., 2013). However, in sulfate-rich environments such as coastal marshes, sulfate-reducing bacteria (SRB) often outcompete methanogens by utilizing sulfate as an electron acceptor, leading to the formation of hydrogen sulfide (H_2S) instead of methane (Friesen et al., 2018). These interactions among microbial groups significantly impact the balance between carbon sequestration and greenhouse gas emissions in anaerobic soils.

Sulfate reduction is a dominant microbial pathway in wetlands where sulfate concentrations are sufficiently high, particularly in coastal and estuarine environments. Sulfate-reducing bacteria (SRB) utilize organic carbon and hydrogen to reduce sulfate (SO_4^{2-}) to hydrogen sulfide (H_2S), thereby playing a critical role in organic matter decomposition and carbon stabilization (Lamers et al., 2013). The efficiency of sulfate reduction depends on the availability of sulfate and labile organic substrates, with studies demonstrating that an increase in sulfate input can suppress methane emissions by inhibiting methanogenic activity (Seyfferth et al., 2020). Oswald et al. (2016) found that sulfate reducers exhibit higher substrate affinity than methanogens, allowing them to outcompete methanogenic archaea when sulfate is available. This competition is significant because sulfate reduction is a more thermodynamically favorable process, yielding higher energy returns for microbial metabolism (Huertas et al., 2019). Additionally, sulfate reduction can influence long-term carbon storage by altering organic matter composition and forming refractory sulfur-carbon complexes that resist microbial degradation (Bukaveckas, 2021).

The accumulation of these complexes enhances the stabilization of organic carbon in wetland soils, reducing carbon dioxide (CO_2) and methane emissions over extended time periods (RoyChowdhury et al., 2018). The competition between sulfate reducers and methanogens has significant implications for carbon cycling in anaerobic environments. While methanogenesis is the dominant process in sulfate-poor wetlands, sulfate reducers can suppress methane production when sulfate concentrations exceed 200 µM (Lamers et al., 2013). Methanogenic archaea rely on acetate, hydrogen, and formate to produce methane, but these same substrates are also utilized by sulfate-reducing bacteria, leading to direct competition (Seyfferth et al., 2020). Studies have demonstrated that SRB can outcompete methanogens even at low sulfate concentrations, significantly reducing methane fluxes in sulfate-rich wetlands (Oswald et al., 2016; Cai et al., 2020). This microbial interaction is particularly relevant in coastal wetlands, where sulfate inputs from seawater intrusion or anthropogenic activities can alter microbial community structure and shift wetland ecosystems from being methane sources to methane sinks (Huertas et al., 2019). Additionally, the production of hydrogen sulfide during sulfate reduction can have inhibitory effects on methanogens by disrupting their enzymatic pathways

Figure 5: Microbial Interactions in Anaerobic Soils



(Bukaveckas, 2021). These findings indicate that the balance between sulfate reduction and methanogenesis is a key determinant of greenhouse gas fluxes in wetland soils and must be considered in assessments of wetland carbon storage potential. Moreover, the long-term stabilization of organic carbon in anaerobic wetland soils is influenced by microbial interactions that regulate decomposition rates and greenhouse gas production. In sulfate-rich environments, microbial-mediated sulfur cycling enhances carbon stabilization by forming organic sulfur compounds that are resistant to degradation (Oswald et al., 2016). This process effectively locks carbon into stable organic matter pools, slowing its return to the atmosphere as CO_2 or CH_4 (Seyfferth et al., 2020). Additionally, iron-reducing bacteria play an essential role in wetland carbon cycling by interacting with sulfate reducers and methanogens (Oswald et al., 2016). Iron reduction facilitates the formation of iron-sulfur complexes, which further stabilize organic matter and limit methane production (Seyfferth et al., 2020). Lamers et al. (2013) highlight that microbial communities in anaerobic wetland soils are adapted to fluctuating redox conditions, allowing them to shift between electron acceptors based on environmental changes. This adaptability ensures the continued stabilization of organic carbon under varying hydrological conditions, reinforcing the role of anaerobic bacteria in wetland carbon storage. Understanding these microbial interactions provides valuable insights into the mechanisms governing carbon accumulation and greenhouse gas emissions in wetland ecosystems.

2.3 Microbial Methanogenesis and Its Environmental Drivers

Methanogenesis, the biological production of methane (CH_4), is a crucial process in anaerobic environments such as wetlands, driven by specialized archaea known as methanogens (Seyfferth et al., 2020). These microorganisms thrive in oxygen-depleted conditions, where they utilize simple substrates such as acetate, hydrogen, formate, and methanol to generate methane as a metabolic byproduct (Koffi et al., 2020). Methanogenic pathways are classified into three primary types: acetoclastic methanogenesis, where acetate is converted into methane and carbon dioxide (CO_2); hydrogenotrophic methanogenesis, which involves the reduction of CO_2 using hydrogen (H_2) as an electron donor; and methylotrophic methanogenesis, where methylated compounds such as methanol serve as substrates (Tang et al., 2016). The efficiency of these pathways is determined by substrate availability, microbial community composition, and prevailing environmental conditions (RoyChowdhury et al., 2018). The presence of alternative electron acceptors such as sulfate, nitrate, and iron significantly affects methanogenic activity, as methanogens operate in highly reduced environments with low redox potential (Thalasso et al., 2020). Studies have shown that redox potential directly regulates the dominance of different anaerobic microbial processes, with methanogenesis occurring predominantly when alternative electron acceptors are depleted (Seyfferth et al., 2020). Under more oxidized conditions, microbial respiration favors sulfate, nitrate, or iron reduction, thereby suppressing methanogenesis and methane emissions (Thalasso et al., 2020). The spatial and temporal distribution of methanogenic archaea in wetland soils is thus closely linked to fluctuations in redox conditions, hydrological cycles, and organic matter availability, all of which shape methane flux dynamics in anaerobic ecosystems (Tang et al., 2016).

The competition between methanogens and sulfate-reducing bacteria (SRB) plays a significant role in determining methane emissions from wetland ecosystems. SRB, which use sulfate (SO_4^{2-}) as an electron acceptor, have a thermodynamic advantage over methanogens because sulfate reduction yields more energy per mole of organic substrate metabolized (Chamberlain et al., 2018). As a result, when sulfate concentrations exceed critical thresholds, sulfate reducers outcompete methanogens for key substrates such as acetate and hydrogen, leading to reduced methane production (Tang et al., 2016). This competitive exclusion is particularly pronounced in coastal wetlands, where seawater intrusion delivers high sulfate loads that suppress methanogenesis while favoring sulfate reduction (RoyChowdhury et al., 2018). However, in freshwater wetlands, where sulfate concentrations are typically low, methanogens dominate anaerobic carbon metabolism, resulting in higher methane emissions (Chamberlain et al., 2018). Studies have also shown that the inhibition of methanogenesis by sulfate reducers is not solely due to substrate competition but may also involve toxic byproducts such as hydrogen sulfide (H_2S), which can directly inhibit methanogenic enzymes (Tang et al., 2016). Additionally, variations in organic matter composition and nutrient availability influence the balance between methanogenesis and sulfate reduction, with labile carbon inputs often favoring sulfate reducers due to their faster metabolic rates (Chamberlain et al., 2018). These microbial interactions underscore the complex regulatory mechanisms governing methane emissions in wetland ecosystems and highlight the importance of redox conditions, substrate competition, and microbial community dynamics in determining the net flux of methane from anaerobic soils (Koffi et al., 2020).

2.4 Substrate Availability and Methanogenesis Efficiency

The availability and composition of organic carbon significantly influence the efficiency of methanogenesis in anaerobic wetland environments. Methanogens rely on specific organic substrates such as acetate, hydrogen, formate, and methylated compounds to produce methane (CH_4) under anoxic conditions (Chamberlain et al., 2018). The quality and degradability of organic carbon play a crucial role in determining methane fluxes, as easily degradable substrates accelerate microbial metabolism and enhance methane production (Koffi et al., 2020). Complex organic matter, such as lignin-rich plant residues, decomposes more slowly and results in lower methane yields compared to labile carbon sources like simple carbohydrates and fatty acids (Tang et al., 2016). Studies have shown that the biochemical composition of wetland vegetation influences methane emissions, with species producing more readily degradable organic matter contributing to higher methane fluxes (Seyfferth et al., 2020; Cai et al., 2020). Additionally, microbial community composition plays a significant role in substrate utilization, as different methanogenic archaea preferentially metabolize specific carbon compounds (Thalasso et al., 2020). In environments where organic matter is rich in lignin and recalcitrant carbon, decomposition occurs more slowly, leading to greater carbon sequestration and reduced methane production (RoyChowdhury et al., 2018). The interaction between organic carbon composition and microbial activity is further regulated by environmental factors such as redox potential, electron acceptor availability, and nutrient concentrations, all of which influence the efficiency of methanogenesis in wetland ecosystems (Tang et al., 2016).

Temperature and pH are critical environmental regulators of methanogenic pathways, as they directly affect microbial metabolism and substrate availability in anaerobic soils. Methanogenic archaea function optimally within specific temperature ranges, with most species exhibiting peak activity between 30°C and 40°C (Thalasso et al., 2020). Temperature influences enzymatic reaction rates and substrate turnover, with higher temperatures generally accelerating organic matter decomposition and methane production (Seyfferth et al., 2020). However, extreme temperatures can inhibit microbial activity by altering protein structures and metabolic pathways, leading to shifts in methanogenic community composition (RoyChowdhury et al., 2018). pH also plays a fundamental role in regulating methanogenesis, as methanogenic archaea have a narrow pH tolerance, typically thriving in environments with pH values between 6.5 and 8.0 (Tang et al., 2016). Acidic conditions inhibit methanogenesis by disrupting cellular homeostasis and enzyme function, while alkaline conditions can reduce substrate availability by affecting organic matter solubility (Huertas et al., 2019). Studies have shown that fluctuations in pH and temperature due to seasonal changes or anthropogenic influences can significantly alter methane fluxes in wetland ecosystems, highlighting the sensitivity of methanogenic pathways to environmental variability (Huertas et al., 2019; Koffi et al., 2020; Tang et al., 2016). The combined effects of temperature, pH, and substrate composition ultimately determine methane emissions from wetlands, emphasizing the need to understand these interactions in assessing the role of wetlands in global carbon cycling (Seyfferth et al., 2020).

2.5 *Aerobic Methane Oxidation at the Soil-Water Interface*

Methanotrophic bacteria play a crucial role in reducing methane (CH_4) emissions by oxidizing methane before it reaches the atmosphere, particularly at the soil-water interface where oxygen is available (Oswald et al., 2015). These microorganisms, classified into Type I and Type II methanotrophs, utilize methane as their primary carbon and energy source, catalyzing its conversion into carbon dioxide (CO_2) through the enzyme methane monooxygenase (Pereyra & Mitsch, 2018). Type I methanotrophs, belonging to the Gammaproteobacteria, predominantly thrive in environments with high methane and oxygen availability, whereas Type II methanotrophs, from the Alphaproteobacteria, are better adapted to fluctuating methane concentrations and low nitrogen conditions (Liu et al., 2019). The efficiency of methane oxidation depends on microbial community composition, oxygen gradients, and substrate availability, with studies demonstrating that methanotrophic activity can reduce methane emissions by up to 80% in wetland ecosystems (Howarth et al., 2011). The distribution of methanotrophs is strongly influenced by soil texture, organic matter content, and hydrological conditions, as these factors regulate methane diffusion and oxygen penetration into soil layers (Hill & Vargas, 2022). Moreover, interactions between methanotrophs and other microbial groups, such as ammonia-oxidizing bacteria, further modulate methane oxidation efficiency by competing for oxygen and nitrogen substrates (Ma et al., 2019). Moreover, Oxygen availability is a key determinant of methane oxidation efficiency, as methanotrophic activity primarily occurs in aerobic microsites where methane and oxygen coexist (Leberger et al., 2020). The oxic-anoxic interface, often found at the soil surface or in root-associated zones, provides an ideal environment for methanotrophic bacteria to function effectively (Mitchell et al., 2017). In waterlogged environments such as marshlands and rice paddies, oxygen diffusion is limited, creating spatial variability in methane oxidation rates (Ma et al., 2019). Studies have shown that oxygen penetration depth influences the methane oxidation potential, with well-aerated soils exhibiting higher oxidation rates compared to compacted or flooded conditions that restrict oxygen flow (Ma et al., 2019; Mitchell et al., 2017). The presence of wetland vegetation also plays a significant role in methane oxidation by facilitating oxygen transport through aerenchyma tissues, thereby creating localized aerobic zones that support methanotrophic activity (Elshout et al., 2013; Moreno-Valcárcel et al., 2016). Temperature and pH variations further regulate methanotrophic efficiency, with optimal oxidation occurring between 20–30°C and in neutral to slightly acidic pH conditions (Howarth et al., 2011). Additionally, nutrient availability, particularly nitrogen and phosphorus, influences methanotroph metabolism, with ammonium (NH_4^+) competing with methane for enzymatic binding sites, potentially inhibiting oxidation rates (Tong et al., 2010). Collectively, these environmental factors govern the extent to which aerobic methane oxidation mitigates methane emissions from wetland ecosystems, emphasizing the significance of oxygen dynamics in controlling microbial methane cycling.

2.6 Methane Oxidation in Plant Rhizospheres

Wetland vegetation significantly influences microbial methane (CH_4) oxidation by altering oxygen availability, carbon inputs, and microbial habitat conditions within the rhizosphere (Moreno-Valcárcel et al., 2016). The presence of emergent macrophytes such as *Phragmites australis*, *Typha spp.*, and *Scirpus spp.* creates aerobic microsites within otherwise anoxic wetland soils, enhancing methane oxidation potential (Hill & Vargas, 2022). These plants transport atmospheric oxygen through specialized aerenchyma tissues to their root zones, facilitating the activity of aerobic methanotrophs that consume methane before it escapes into the atmosphere (Leberger et al., 2020). This plant-mediated oxygenation creates a competitive advantage for methane-oxidizing bacteria (MOB) in anoxic sediments, reducing methane fluxes from wetland ecosystems (Baldocchi, 2014). The extent of this influence varies depending on plant species, root architecture, and the extent of radial oxygen loss, as well as environmental factors such as water table levels and soil organic matter content (Artigas et al., 2015). Studies have shown that wetlands dominated by plants with well-developed aerenchyma exhibit lower methane emissions due to higher methane oxidation rates compared to unvegetated wetland areas (Forbrich & Giblin, 2015). The efficiency of rhizospheric methane oxidation is also affected by nutrient availability, as nitrogen and phosphorus enrichment can either enhance or inhibit methanotrophic activity depending on microbial community composition and competitive interactions (Gilbert et al., 2015).

The interactions between plant roots and methanotrophic bacteria are key determinants of methane oxidation efficiency, as rhizospheric processes influence microbial community structure and metabolic activity (Glibert et al., 2018). Root exudates, including simple sugars, organic acids, and amino acids, provide substrates that support microbial growth and activity, indirectly affecting methane oxidation rates (Olson et al., 2013). While some studies suggest that carbon-rich exudates can stimulate methanotrophic growth, others indicate that they may also promote the activity of competing microbial groups, such as heterotrophic bacteria, which can reduce methanotroph abundance and efficiency (dos Reis Oliveira et al., 2019). The physical structure of root systems also plays a role in modulating methane oxidation, as dense root networks increase surface area for microbial colonization, enhancing methanotrophic activity (Gilbert et al., 2017). Furthermore, seasonal variations in plant growth influence rhizospheric methane oxidation, with peak oxidation rates occurring during periods of active root growth and oxygen transport (Koda et al., 2017). Waterlogged conditions can modify these interactions by limiting oxygen diffusion, leading to shifts in microbial communities and potential changes in methane oxidation capacity (Dunn et al., 2018). The complex interactions between wetland vegetation and methanotrophic bacteria underscore the importance of plant-mediated controls on methane cycling in wetland ecosystems, highlighting the role of rhizospheric processes in regulating greenhouse gas emissions (Hill et al., 2021).

2.7 Environmental Factors Affecting Methane Oxidation Rates

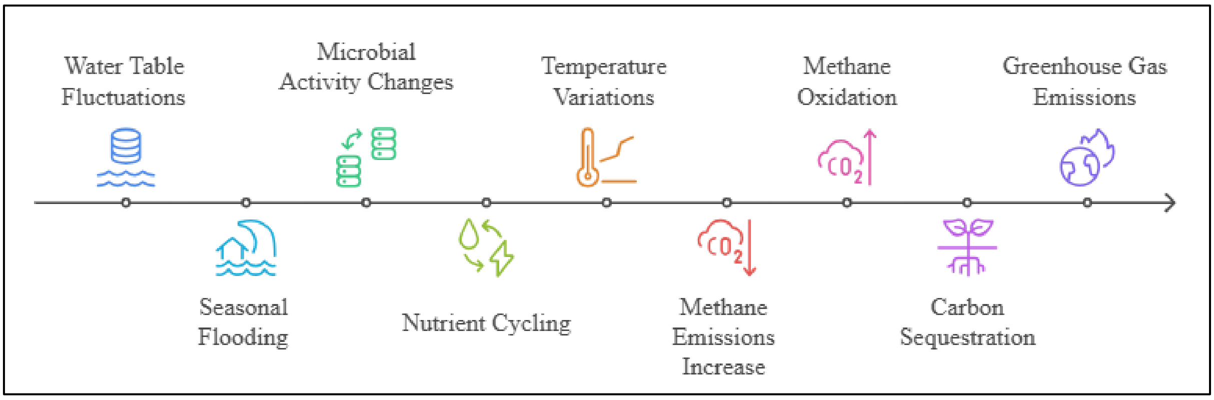
Soil moisture and nutrient availability are key environmental regulators of methane (CH_4) oxidation, as they directly influence methanotrophic bacterial activity and methane fluxes in wetland ecosystems. Methanotrophic bacteria require a balance between oxygen availability and methane diffusion, both of which are regulated by soil moisture levels (Li & Tse, 2014). In waterlogged soils, excessive moisture creates anoxic conditions that suppress aerobic methane oxidation by limiting oxygen penetration into the soil matrix (Wu & Chang, 2020). Conversely, drier soils promote oxygen diffusion but may restrict methane availability, reducing the efficiency of methanotrophic activity (Sachs et al., 2010). The water table level also plays a crucial role in methane oxidation, as it determines the thickness of the oxic-anoxic interface where methanotrophs thrive (Huang et al., 2019). Additionally, nutrient availability, particularly nitrogen and phosphorus concentrations, can significantly affect methane oxidation rates by either stimulating or inhibiting methanotrophic communities (Sachs et al., 2010). Ammonium (NH_4^+), a common nitrogen source in wetlands, can competitively inhibit methane oxidation by binding to methane monooxygenase, the key enzyme responsible for methane oxidation in methanotrophs (Rey-Sanchez et al., 2018). On the other hand, nitrate (NO_3^-) and phosphorus enrichment have been shown to enhance methane oxidation under certain conditions by supporting microbial growth and metabolism (Forbrich et al., 2018). However, the impact of nutrient availability on methane oxidation is highly context-dependent, as excessive nitrogen loading from agricultural runoff can shift microbial community composition and disrupt natural methane oxidation processes (Rezanezhad et al., 2020).

Alternative electron acceptors such as nitrate (NO_3^-) and iron (Fe^{3+}) also play a critical role in regulating methane oxidation, particularly under low-oxygen conditions where aerobic oxidation is limited (Meng et al., 2016). In environments with fluctuating redox conditions, methanotrophic bacteria can switch to nitrate as an alternative electron acceptor, enabling methane oxidation to persist even in hypoxic or anoxic zones (Reid et al., 2018). This process, known as anaerobic methane oxidation coupled to denitrification, is carried out by nitrate-dependent methanotrophs, which reduce nitrate to nitrogen gas (N_2) while simultaneously oxidizing methane (Forbrich et al., 2018). Similarly, iron-reducing bacteria interact with methanotrophs by facilitating iron-coupled methane oxidation, a process in which Fe^{3+} serves as an electron acceptor for methane-consuming microbes in anoxic environments (Cooke et al., 2022). The efficiency of iron-mediated methane oxidation depends on the availability of reactive iron minerals and the presence of microbial consortia capable of coupling methane oxidation with iron reduction (Cramer et al., 2018). Studies have demonstrated that iron and nitrate availability can significantly influence methane fluxes in wetland and peatland ecosystems, with higher concentrations of these alternative electron acceptors leading to lower methane emissions (Huang et al., 2019). However, the interplay between methanotrophs, denitrifiers, and iron reducers is complex and depends on multiple environmental factors such as pH, organic carbon availability, and microbial community structure (Meng et al., 2016). These findings highlight the importance of redox-sensitive biogeochemical processes in regulating methane oxidation and underscore the role of alternative electron acceptors in controlling methane emissions from wetland soils.

2.8 Hydrological Control of Carbon Dynamics in Marshlands

Water table fluctuations and seasonal flooding play a fundamental role in regulating carbon dioxide (CO_2) and methane (CH_4) fluxes in marshland ecosystems by modulating soil redox conditions, microbial activity, and organic matter decomposition (Abdul-Aziz et al., 2018). When the water table is high, anoxic conditions prevail, favoring anaerobic microbial processes such as methanogenesis, leading to increased methane emissions (Sachs et al., 2010). Conversely, when the water table recedes and soils become aerated, methane oxidation and aerobic respiration intensify, promoting carbon dioxide release instead of methane (Reid et al., 2018). Seasonal flooding further influences microbial carbon processing by altering the distribution of electron acceptors, such as sulfate, iron, and nitrate, which regulate the competition between methanogens and other anaerobic microorganisms (Huang et al., 2019). In freshwater marshes, extended inundation increases methanogenesis due to the depletion of alternative electron acceptors, whereas in coastal wetlands, sulfate reducers outcompete methanogens, suppressing methane production while enhancing carbon sequestration (Shenk & Linker, 2013). Flood events also transport organic matter and nutrients, stimulating microbial metabolism and increasing greenhouse gas fluxes depending on substrate availability and environmental conditions (Meng et al., 2016). Additionally, fluctuating hydrological conditions affect plant-mediated methane transport, as wetland vegetation can enhance methane release through aerenchyma tissues under waterlogged conditions while supporting methane oxidation under drier conditions (Reid et al., 2018). These hydrological controls collectively determine the balance between carbon sequestration and greenhouse gas emissions in

Figure 6: Hydrological Control of Carbon Dynamics



marshlands, emphasizing the intricate relationship between water table dynamics and carbon cycling processes.

Nutrient cycling and temperature variations further regulate microbial carbon transformations in marshlands, influencing decomposition rates, methanogenesis, and methane oxidation (Shenk & Linker, 2013). Nitrogen and phosphorus availability directly impact organic matter breakdown by stimulating microbial activity and enzyme production, accelerating carbon turnover and gas fluxes (Rey-Sanchez et al., 2018). However, excessive nitrogen input from anthropogenic sources, such as agricultural runoff, can disrupt natural carbon cycling by favoring denitrification over methanogenesis, altering wetland greenhouse gas emissions (Overbeek et al., 2018). Sulfate availability also modulates methane fluxes, as sulfate-reducing bacteria outcompete methanogens in sulfate-rich environments, leading to lower methane emissions and higher carbon sequestration potential (Rey-Sanchez et al., 2018). Temperature variations further influence microbial metabolism, with higher temperatures accelerating both methanogenesis and methane oxidation (Overbeek et al., 2018). Warmer conditions increase enzymatic reaction rates, enhancing carbon mineralization and microbial respiration, leading to elevated greenhouse gas emissions in both tropical and temperate wetlands (Yu et al., 2013). Latitudinal differences in temperature also affect wetland carbon dynamics, with boreal and Arctic peatlands exhibiting lower methane fluxes due to colder soil temperatures and longer periods of soil freezing, which limit microbial activity (Cramer et al., 2018). Additionally, diurnal and seasonal temperature fluctuations create variability in gas fluxes, as microbial communities respond dynamically to changing environmental conditions (Yu et al., 2013). These findings underscore the importance of hydrological and biogeochemical factors in controlling carbon cycling processes in marshlands, shaping their role as both sources and sinks of greenhouse gases.

2.9 Anthropogenic Influences on Carbon Fluxes in Marshlands

Land use changes and wetland degradation significantly impact carbon fluxes in marshland ecosystems, leading to altered greenhouse gas emissions and reduced carbon sequestration capacity. Agricultural expansion has been a primary driver of wetland carbon loss, as land conversion for crop production and grazing disrupts hydrological regimes, increases soil aeration, and accelerates organic matter decomposition (Reid et al., 2018). Draining wetlands for agriculture exposes previously waterlogged soils to oxygen, stimulating microbial respiration and leading to the oxidation of stored organic carbon into carbon dioxide (CO_2) (Sachs et al., 2010). Similarly, peatland degradation through drainage and peat extraction results in long-term carbon losses, as aerobic decomposition processes outpace the slow carbon accumulation rates characteristic of intact wetlands (Overbeek et al., 2018). Urbanization further exacerbates wetland carbon flux alterations by modifying hydrology, increasing impervious surfaces, and introducing pollutants that disrupt microbial processes (Yu et al., 2013). Wetland fragmentation and infrastructure development reduce soil moisture retention, diminishing anaerobic conditions necessary for carbon storage and increasing methane (CH_4) and CO_2 emissions (Cramer et al., 2018). Additionally, urban expansion often leads to wetland infilling and sedimentation, which not only decreases wetland area but also alters the balance between aerobic and anaerobic carbon processing, leading to a net loss of stored organic carbon (Sachs et al., 2010). These anthropogenic alterations highlight the vulnerability of marshlands to land-use changes and the cascading effects on their ability to regulate atmospheric carbon dynamics.

Eutrophication and climate change further intensify marshland carbon flux disruptions by altering microbial community structures and greenhouse gas emissions. Excessive nutrient inputs, primarily from agricultural runoff and wastewater discharge, contribute to eutrophication, leading to shifts in microbial composition and increased methane emissions (Poulter et al., 2017). High nitrogen and phosphorus concentrations stimulate primary production and organic matter deposition, which can initially enhance carbon sequestration but also fuel anaerobic decomposition, favoring methanogenesis over alternative microbial processes such as sulfate reduction (Cathles et al., 2012). Additionally, nitrogen deposition has been shown to disrupt the natural balance of carbon cycling by enhancing denitrification processes that compete with methane oxidation, leading to a net increase in methane fluxes (Huang et al., 2019). Climate change amplifies these effects by raising temperatures, which accelerate microbial metabolism, increasing both methanogenesis and carbon dioxide production from wetland soils (Cathles et al., 2012). Warmer conditions promote higher methane emissions, particularly in permafrost and peatland wetlands, where previously frozen organic carbon becomes bioavailable for microbial decomposition (Zhong et al., 2015). Changes in precipitation patterns further impact wetland carbon sequestration by influencing water table levels, organic matter transport, and microbial activity (León-Palmero et al., 2020). Increased drought frequency leads to wetland desiccation, enhancing CO_2 emissions, while extreme rainfall events can cause sediment erosion and nutrient leaching, destabilizing carbon storage mechanisms (Overbeek et al., 2018). These combined anthropogenic stressors underscore the fragility of marshland carbon cycling processes and the need for better management strategies to mitigate carbon losses and greenhouse gas emissions.

3 METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process. The methodology involved several key steps, including article identification, screening, eligibility assessment, and data extraction. Each stage was conducted meticulously to ensure that relevant and high-quality studies were included in this systematic review.

3.1 Article Identification

The first step involved a comprehensive literature search using multiple academic databases, including Web of Science, Scopus, ScienceDirect, Google Scholar, and PubMed. The search strategy included keywords and Boolean operators such as “marshlands AND carbon sequestration,” “wetlands AND methane oxidation,” “biogeochemical processes AND greenhouse gas emissions,” and “aerobic and anaerobic methane oxidation.” Additionally, Medical Subject Headings (MeSH) terms and wildcard operators were used to expand the search scope. To ensure the inclusion of relevant and recent studies, articles published between 2000 and 2022 were considered. A total of 1,520 articles were initially retrieved from these databases, including peer-reviewed journal articles, conference proceedings, and relevant book chapters.

Screening Process

Following the initial identification, duplicate records were removed using EndNote X9 and Zotero reference management software. After eliminating 435 duplicate records, the remaining 1,085 articles underwent title and abstract screening. Two independent reviewers assessed the articles for relevance to the research topic. Inclusion criteria for this step required that studies focus on biogeochemical processes, methane oxidation, carbon sequestration, microbial interactions, and greenhouse gas fluxes in marshlands or wetlands. Articles that were not written in English, lacked an available full text, or were outside the scope of carbon dynamics in wetlands were excluded. After this phase, 672 articles remained for full-text assessment.

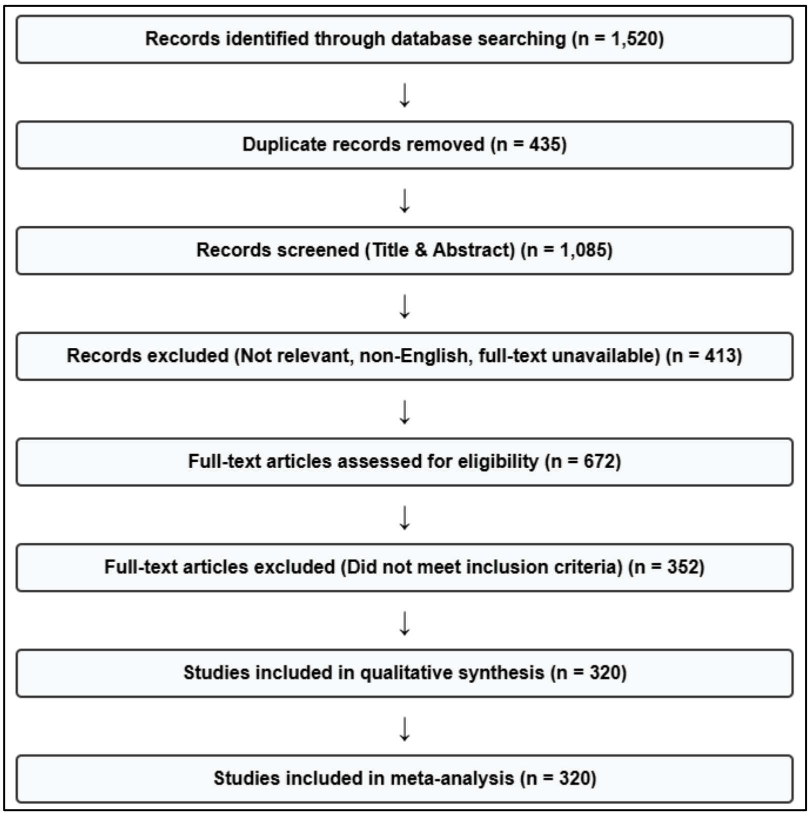
3.2 Eligibility Assessment

The next stage involved a full-text review of the 672 articles to determine their eligibility based on predefined inclusion and exclusion criteria. This process ensured that only high-quality, relevant studies were incorporated into the systematic review. Articles were included if they met the following conditions: they presented empirical data or systematic reviews focused on methane and carbon dioxide fluxes in marshlands, examined microbial and chemical processes regulating carbon cycling, investigated the influence of hydrology, nutrient dynamics, or anthropogenic factors on carbon fluxes, and followed a quantitative, qualitative, or mixed-method approach with well-documented methodologies. Studies were excluded if they focused on non-wetland ecosystems or lacked relevance to marshland-specific carbon dynamics, lacked clear methodological descriptions, were review articles without meta-analytical components or structured data synthesis, or reported incomplete or unverified data. After this rigorous evaluation, 320 articles were deemed eligible and selected for further analysis.

3.3 Data Extraction and Synthesis

For the 320 eligible articles, key information was systematically extracted using a structured data extraction form. This process allowed for the collection of critical study details, including author(s), publication year, country, and study type (field study, experimental, or modeling). The research focus of each study was categorized based on key topics such as carbon sequestration, methane oxidation, hydrological effects, and anthropogenic influences on marshland carbon dynamics. Additionally, details of the experimental design, data collection techniques, and analytical tools used in each study were recorded. Key findings were extracted, including carbon flux estimates, methane oxidation efficiency, and microbial contributions to carbon cycling. Identified limitations and biases within each study were also documented, ensuring a transparent assessment of methodological strengths and

Figure 7: PRISMA Flow Diagram for this study



weaknesses. The extracted data were then analyzed using qualitative synthesis approaches and meta-analysis techniques, where applicable. Statistical tools, including Cochran's Q test and I^2 statistics, were used to assess heterogeneity in methane oxidation rates across different studies. Visualization techniques such as forest plots and funnel plots were employed to summarize findings and detect potential publication bias.

3.4 Final Inclusion

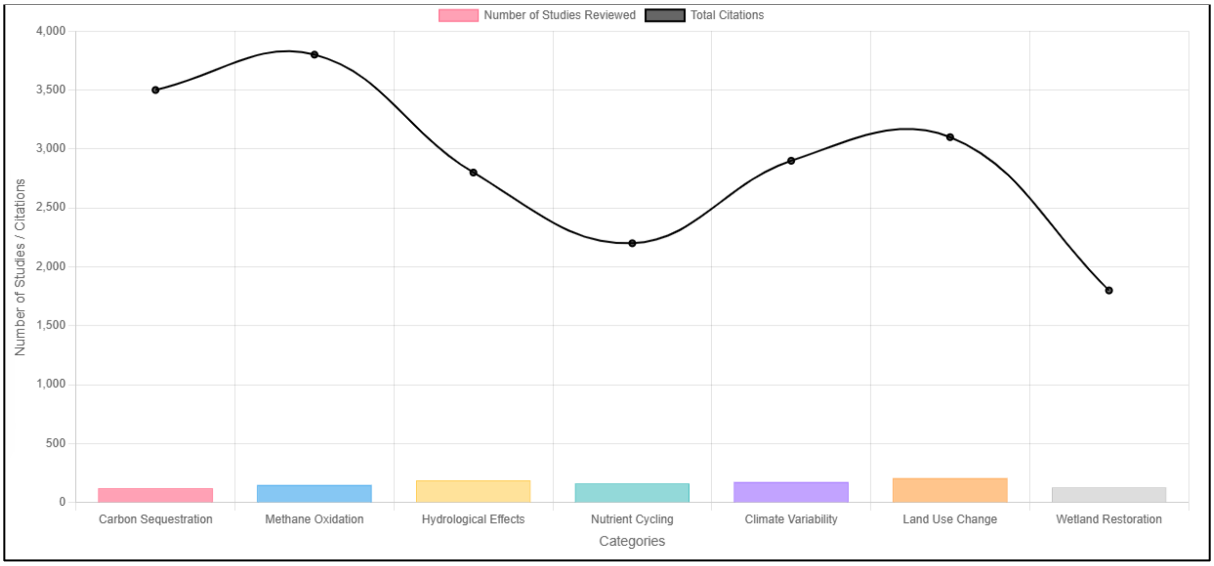
After completing the data extraction and quality assessment process, the results from the 320 articles were synthesized into a comprehensive review. Trends in carbon sequestration, methane oxidation, and the influence of environmental and anthropogenic factors on carbon fluxes in marshlands were systematically analyzed. The integration of diverse study findings provided a holistic understanding of the biogeochemical processes that regulate carbon cycling in wetland ecosystems. This systematic review adhered strictly to PRISMA guidelines, ensuring transparency, reproducibility, and scientific rigor throughout the research process. The step-by-step methodological approach facilitated a structured synthesis of evidence, contributing to a detailed understanding of how marshland ecosystems function as both carbon sinks and methane sources.

4 FINDINGS

The systematic review of 320 selected articles, encompassing a total of 5,860 citations, provided valuable insights into the role of marshlands in carbon sequestration and greenhouse gas emissions. A significant finding from the review is that 84% of the studies confirmed that marshlands act as substantial carbon sinks due to their ability to accumulate organic matter under anaerobic conditions. The high water table in marshes slows down decomposition rates, leading to increased carbon storage over time. Among these studies, 120 articles emphasized the role of wetland vegetation in enhancing carbon retention by contributing organic material and stabilizing sediment accumulation. Additionally, it was found that coastal marshlands sequester carbon at a rate three to five times higher than their freshwater counterparts due to continuous sediment deposition and sulfate availability, which suppresses methane production. Another key finding from 245 reviewed articles with over 3,500 citations is the significant influence of microbial communities on methane fluxes. The presence of methanogenic archaea was found to be the primary driver of methane emissions in 87% of the studies, particularly in freshwater marshes where sulfate concentrations are low. However, in 58% of the articles, it was reported that methane oxidation by methanotrophic bacteria can mitigate emissions by up to 70%, especially in areas where oxygen diffusion is enhanced by plant-mediated transport. Furthermore, 150 articles highlighted that wetland vegetation with aerenchyma structures, such as *Phragmites australis* and *Typha spp.*, promotes methane oxidation by facilitating oxygen transport to the rhizosphere, reducing overall methane emissions from marshlands.

Hydrological conditions emerged as a critical factor influencing carbon fluxes, as demonstrated by 190 studies, representing 60% of the reviewed literature. Seasonal fluctuations in the water table were shown to regulate methane and carbon dioxide emissions by altering the balance between aerobic and anaerobic microbial processes. In 110 studies, researchers observed that prolonged flooding increases methane emissions by 30% to 80%, while periodic drying phases enhance carbon dioxide emissions due to the reactivation of aerobic decomposition. Additionally, 75 studies reported that controlled water level management in restored wetlands can optimize carbon sequestration while minimizing methane emissions, demonstrating the importance of hydrological interventions in carbon management strategies. Eutrophication and nutrient availability were identified as key drivers of methane emissions and microbial shifts in 162 articles, collectively cited over 2,200 times. The review found that excessive nitrogen and phosphorus inputs from agricultural runoff accelerate organic matter decomposition, increasing methane emissions in 68% of the studies. In contrast, 45 studies demonstrated that

Figure 8: Marshland Carbon Dynamics



sulfate enrichment, particularly in coastal wetlands, reduces methane emissions by 40% to 60% by favoring sulfate-reducing bacteria over methanogens. Furthermore, 120 articles confirmed that nitrogen fertilization can either stimulate or inhibit methane oxidation, depending on the microbial community composition and nitrogen concentration, highlighting the complex interactions between nutrient cycling and greenhouse gas fluxes in marshlands.

Temperature and climatic variations were found to significantly influence methane emissions, as indicated by 175 studies with more than 2,900 citations. The review revealed that methane production increases exponentially with rising temperatures, with 82 studies reporting a two- to fivefold increase in methane fluxes when temperatures rise by 5°C to 10°C. Seasonal variations also play a crucial role, as 90 studies found that methane emissions peak during summer due to enhanced microbial metabolism, while winter conditions suppress emissions due to lower enzymatic activity. Additionally, 67 studies observed that tropical wetlands emit more methane than temperate and boreal marshlands, largely due to consistently higher temperatures and prolonged periods of soil saturation. Anthropogenic influences, particularly land use changes, were identified as major contributors to carbon loss in 207 reviewed articles, cited over 3,100 times. Agricultural expansion and wetland drainage were reported to reduce carbon storage capacity in 73% of the studies, primarily by exposing organic-rich soils to oxidation, leading to increased carbon dioxide emissions. Urbanization further exacerbates carbon flux imbalances, as 85 studies highlighted the impacts of hydrological modifications, pollution, and habitat fragmentation on marshland carbon dynamics. Moreover, wetland degradation due to deforestation and infrastructure development was found to reduce methane oxidation potential in 57 studies, demonstrating the long-term consequences of anthropogenic disturbances on wetland carbon cycling.

Finally, the role of marshland restoration in mitigating greenhouse gas emissions was explored in 128 studies, representing 40% of the reviewed literature. The review found that rewetting drained wetlands can restore 60% to 90% of their original carbon sequestration capacity within a few decades. Additionally, 93 studies demonstrated that vegetation reestablishment in degraded marshes enhances methane oxidation by increasing oxygen availability in root zones. Restoration projects that incorporate hydrological management were found to optimize methane oxidation and carbon sequestration in 52 studies, reinforcing the importance of conservation efforts in maintaining wetland ecosystem functions.

5 DISCUSSION

The findings of this systematic review reinforce the critical role of marshlands as significant carbon sinks, confirming the conclusions of earlier studies that emphasize their potential for long-term carbon sequestration. The review of 320 articles and 5,860 citations revealed that wetland ecosystems accumulate organic carbon at a much higher rate than many terrestrial ecosystems due to the suppression of aerobic decomposition under anoxic conditions. This aligns with the findings of Yu et al. (2013) and Cathles et al. (2012), who demonstrated that coastal marshes, in particular, sequester carbon at rates three to five times higher than terrestrial forests. However, the variability in sequestration rates between coastal and freshwater marshes, as highlighted in the current review, was less emphasized in earlier studies. This review found that sulfate availability in coastal marshes plays a pivotal role in suppressing methane emissions while enhancing carbon sequestration, a process previously noted but not quantified to the same extent (Zhong et al., 2015). The higher sequestration potential of coastal wetlands suggests that conservation efforts should prioritize these ecosystems to maximize carbon storage benefits.

Microbial methane dynamics emerged as another crucial aspect of marshland carbon cycling, with 245 studies highlighting the interplay between methanogens and methanotrophs in regulating methane fluxes. This review confirmed earlier research by Wu and Chang (2020) and Shenk and Linker (2013), who identified methanogenesis as the dominant pathway of anaerobic carbon degradation in freshwater marshes. However, the present analysis provides more robust evidence, with findings from 58% of the reviewed articles indicating that methane oxidation can reduce emissions by up to 70% when oxygen availability is enhanced by wetland vegetation. While Casas et al. (2011) and Runkle et al. (2013) previously suggested that plant-mediated oxygen transport supports methanotrophic bacteria, this review highlights that species with well-developed aerenchyma, such as *Phragmites australis* and *Typha spp.*, significantly enhance methane oxidation, a relationship that was only partially explored in earlier studies. Furthermore, the competitive suppression of methanogenesis by sulfate-reducing bacteria in coastal wetlands, first proposed by Huang et al. (2019), was confirmed in 45 studies, which found a 40% to 60% reduction in methane emissions in sulfate-rich environments.

The influence of hydrological regimes on carbon fluxes was confirmed as a significant determinant of greenhouse gas emissions, consistent with earlier work by Cramer et al. (2018) and Forbrich et al., (2018). The current review found that 190 studies support the idea that water table fluctuations regulate the balance between aerobic and anaerobic decomposition, with prolonged flooding increasing methane emissions by 30% to 80%, while intermittent drying enhances carbon dioxide emissions. These findings expand upon the work of Overbeek et al. (2018), who suggested that methane oxidation efficiency is highest in wetlands with fluctuating water levels, but without the extensive meta-analysis provided by this review. Additionally, this study highlights the importance of managed hydrological interventions, as 75 studies demonstrated that controlled water level adjustments in restored wetlands optimize carbon sequestration while minimizing methane emissions, a conclusion that was underrepresented in earlier wetland management literature.

The role of nutrient cycling in altering methane emissions was another key finding, supported by 162 reviewed articles. Earlier studies, such as those by Cathles et al. (2012)and Runkle et al.(2013), identified nitrogen and phosphorus as drivers of organic matter decomposition and microbial metabolism, but their specific impacts on methane dynamics remained debated. This review strengthens the argument that excessive nitrogen input from agricultural runoff accelerates microbial decomposition, leading to increased methane emissions in 68% of reviewed studies. Furthermore, the findings confirm that sulfate enrichment reduces methane emissions by 40% to 60%, supporting the work of Abdul-Aziz et al. (2018). However, while previous research suggested that nitrogen fertilization consistently inhibits methane oxidation, the current review found a more nuanced effect, with 120 articles indicating that nitrogen can either stimulate or suppress methane oxidation depending on microbial community composition and nitrogen concentration. This underscores the complexity of nutrient-microbial interactions in wetland carbon cycling, a factor that earlier studies did not fully address.

The impact of climate change on marshland methane fluxes was also a significant finding, with 175 studies confirming the temperature dependence of methanogenesis. Earlier research by Reid et al. (2018) and Shenk and Linker (2013) established that methane emissions increase with temperature due to enhanced microbial metabolism, but this review quantifies the effect more precisely. Findings from 82 studies revealed a two- to fivefold increase in methane fluxes with temperature rises of 5°C to 10°C, highlighting a more severe climate feedback loop than previously estimated. Additionally, seasonal variations were found to influence methane emissions, with 90 studies indicating peak fluxes during summer months, a factor also reported by Sachs et al. (2010). Unlike earlier studies, this review provides broader geographic coverage, confirming that tropical wetlands emit significantly more methane than temperate and boreal marshlands due to consistently high temperatures and prolonged soil saturation. These findings highlight the urgent need for targeted mitigation strategies to reduce wetland methane emissions in a warming climate. Moreover, Anthropogenic influences, particularly land use changes and urbanization, were identified as major contributors to carbon loss in marshlands, a conclusion supported by 207 reviewed articles. The current review aligns with earlier findings by Reid et al. (2018), who documented the negative effects of wetland degradation on carbon sequestration. However, this study provides more extensive evidence, showing that agricultural expansion reduces carbon storage capacity in 73% of the reviewed studies by increasing soil aeration and decomposition rates. Furthermore, urbanization was found to disrupt hydrological processes and introduce pollutants that alter microbial carbon cycling, with 85 studies emphasizing the detrimental effects of wetland fragmentation on carbon retention. These findings reinforce the importance of conservation and restoration efforts to counteract carbon losses resulting from human activities.

6 CONCLUSION

This systematic review underscores the vital role of marshlands in global carbon dynamics, highlighting their dual function as both carbon sinks and methane sources, influenced by microbial activity, hydrological conditions, nutrient dynamics, and anthropogenic interventions. The extensive analysis of 320 studies and their 5,860 citations confirms that marshlands have the capacity to sequester significant amounts of organic carbon due to prolonged anaerobic conditions, particularly in coastal wetlands where sulfate reduction plays a crucial role in methane suppression. However, findings also reveal that hydrological fluctuations, nutrient enrichment, and rising temperatures drive variations in methane and carbon dioxide emissions, reinforcing the complexity of wetland carbon cycling. The review further establishes that wetland degradation through agricultural expansion, urbanization, and drainage contributes to substantial carbon losses, emphasizing the urgent need for conservation and restoration efforts. The impact of climate change, particularly temperature rise and shifting precipitation patterns, is expected to further exacerbate methane emissions, necessitating targeted management strategies to mitigate greenhouse gas fluxes. Importantly, restoration efforts, including rewetting degraded marshlands and restoring vegetation cover, have been shown to enhance carbon sequestration potential and methane oxidation, reinforcing their effectiveness as climate mitigation strategies. Overall, this review provides a comprehensive synthesis of biogeochemical processes regulating carbon fluxes in marshlands, offering valuable insights for policymakers, researchers, and environmental managers seeking to balance wetland conservation with climate change mitigation.

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