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Strategies for CH_4 Emission Reduction from Lakes: Understanding the Key Driving Factors for CH_4 Production and Lake Restoration

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Abstract

Wetlands are active sites of global carbon processing, unceasingly emitting atmospheric methane. Generation and emission of CH_4 is a complex sequential process involving multiple biochemical steps mediated by an array of diverse microbial communities. Once produced in the sediments, CH_4 may venture into different pathways, depending on which it is either oxidised into CO_2 or released as CH_4 into the atmosphere. The main CH_4 pathways in wetlands are diffusion through the water column, ebullition, and plant-mediated transport. This study addresses the key factors influencing CH_4 production, which is critical for sustainable lake management and restoration to reduce CH_4 emissions. Strategic lake management and restoration plans are essential for reducing CH_4 emissions by controlling key factors. Important factors include depth of water, macrophytic growth, microbial community, availability of substrates, temperature, pH, dissolved oxygen, eutrophication, and several others. These factors have been considered and briefly discussed in the present paper.

Keywords: lake, methane, methanogenesis, methanotrophs, restoration and eutrophication

Introduction

Lakes are stable and non-flowing water bodies open to the atmosphere (USGS, 2018), where the water table rises above the land surface with shallow cover. Wetlands play a key role in the global carbon (C) cycle, regulating emission of other atmospheric greenhouse gas (GHG) including nitrous oxide (Khoiyangbam & Chingangbam, 2022; Kumar, et al., 2011). Despite covering only a small portion of the global land surface (~ 2-6%), wetlands contain a large portion of the world's carbon, ~ $15x10^{14}$ kg (Whiting & Chanton, 2001). Atmospheric CH_4, up to 70-80 %, is biogenic in origin (Le Mer &

Roger, 2001). Due to prevailing anaerobic conditions, C in wetlands is emitted as methane (CH_4) and carbon dioxide (CO_2), and emissions from wetlands constitute the largest natural CH_4 source (Li et al., 2024), contributing about 40% of total annual CH_4 emissions. Global lake CH_4 fluxes are 41.6 ± 18.3 Tg CH_4 yr^{-1}, with approximately 50% of the flux contributed by tropical/subtropical lakes (Johnson et al., 2022). Methane is the second-most important GHG, having 25 times the global warming potential of CO_2 over a 100-year time frame (Chingangbam & Khoiyangbam, 2023). The concentrations of atmospheric CH_4 reached new highs in 2022, with global mean concentrations touching 1923±2 ppb (WMO, 2023). Methane is a "short-term climate forcer" with a comparatively short atmospheric lifespan of ~ 12 years. Lake CH_4 emission is an interplay of two intricate sets of microbial processes: methanogenesis, the generation of CH_4, and methanotrophy, the consumption of CH_4. Only the fraction of CH_4 that escapes oxidation reaches the atmosphere. The key drivers of CH_4 emission in lakes include lake morphometry, siltation rates, sedimentation depth, amount of dissolved organic C, available labile organic substrate, primary productivity, temperature, redox potential, pH, etc. (Waldo et al., 2021). Once generated, CH_4 may traverse through three distinct routes in the water body: the ebullitive pathway, the diffusive pathway, and emissions through aquatic vegetation. Methane traveling in the diffusive pathway gets readily oxidized, sometimes up to 90% (Oremland & Culbertson, 1992). In contrast, CH_4 in the ebullitive pathway can escape oxidation (Bastviken et al., 2004). Although it is quite certain that undisturbed wetlands store C for hundreds of years to millennia, the lifespan of the stored C in the wetlands is quite uncertain (Ezcurra et al., 2016).

Currently, there is an upsurge in interest in curtailing GHG emissions, including CH_4, from lakes to abide by the global commitments for GHG emission reduction. Atmospheric CH_4 concentration has surpassed the concentrations aligned with the Paris Agreement goals to restrict global warming to 1.5 and 2^0 C (Nisbet et al., 2020). A large chunk of CH_4 release from the lake is associated with human activities (Skeie et al. 2023), and it is possible to mitigate them. Towards this end, a rigorous scrutiny of the driving factors of CH_4 emission and a thorough understanding of the factors and their responses to climate change is essential. Sustainable lake management targeting CH_4 emission control and water quality improvement may bring co-lateral benefits and a win-win situation. Strategies for lake CH_4 emission abatement should be multipronged in nature, comprising a gamut of feasible approaches including restriction of ex-situ nutrient inflow, primarily phosphorous and nitrogen through sewage and geological runoffs, adequate aquatic oxygenation, treating and dredging of sediments, mitigating global warming, monitoring pollution and lake health, support wetland research and innovations, control of aquatic weed proliferation, etc. This paper attempts to showcase the critical drivers of CH_4 emissions in lakes and review the factors for sustainable lake management, reducing CH_4 emissions and improving the health of the lakes. The emission of methane from surface waters is often dominated by ebullition (bubbling), a transport mode with high spatiotemporal variability.

Materials and Methods

Literature Search and Data Extraction

A rapid campaign of narrative review of the literature was conducted by scanning articles to synthesize and develop a broad overview of the CH_4 production and consumption in the natural freshwater lake, emphasizing the underlying driving factors. Thematic analysis was conducted, identifying common themes, patterns, and trends in the literature with the goal of achieving a comprehensive understanding of CH_4 emissions to identify research gaps for mitigating the negative impacts. A network analysis is performed to identify the most crucial focus of refined papers. Among the general databases, the Web of Science (WoS) core collection database, with many publications after screening (Fig. 1), was used for bibliometric analysis using VOS-viewer software (version 1.6.19). The keywords were used for search queries, and 262 publication results were found. Each publication contains information such as author, country, citations, documents, sources, *etc*. Keyword co-occurrence analysis was applied to find the frequencies of different keywords throughout the documents. The minimum number of occurrences in the keywords is considered to be 10. Out of 1470 keywords, 62 keywords met the threshold and were analysed. The network and overlay visualization maps were mapped and depicted in Fig. 2 (a & b). Each cluster and cooccurrence keywords are represented by a specific size and colour, and the curved lines connecting them display the anecdote links.

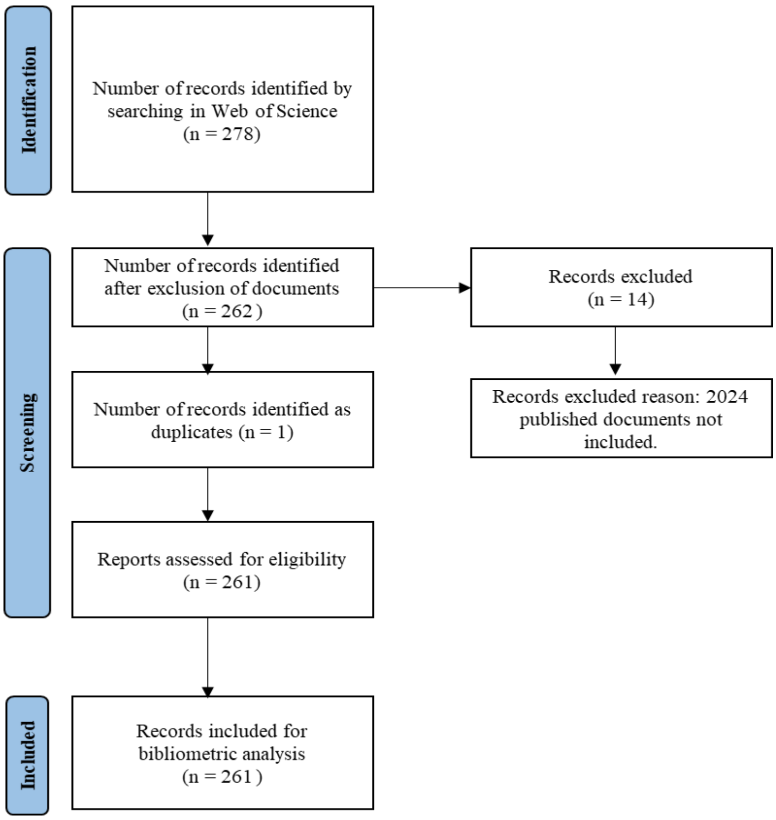

Figure. 1 Flow chart showing the data extraction process

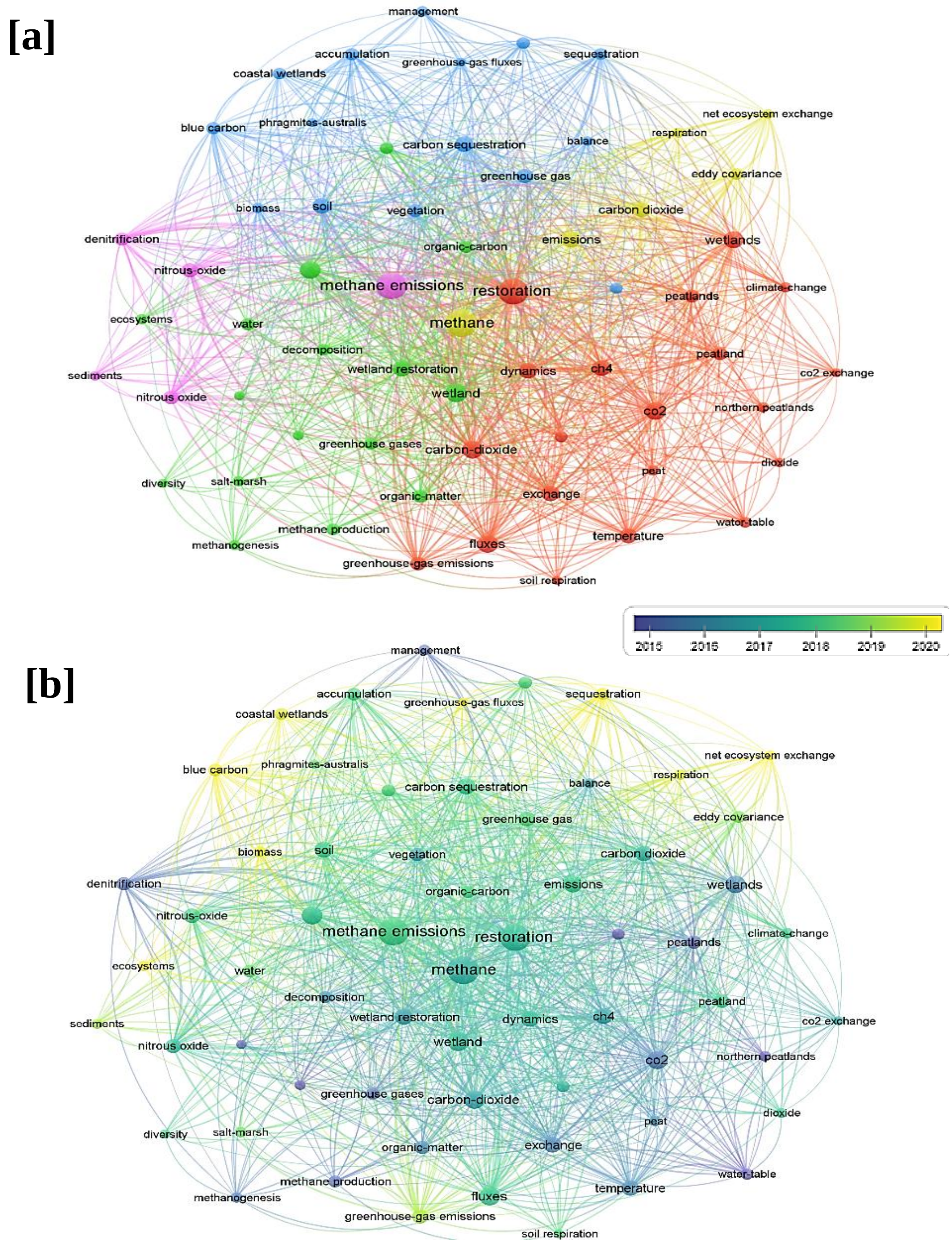

Figure. 2 Co-occurrence Analysis in Terms of All Keywords: **[a]** network visualization map and **[b]** overlay visualization map (1989-2023). The size of the circles is proportional to the weight of the occurrence of the keywords. The strength of the links between the keywords indicates the relationship between the keywords. Similar numbers of co-occurrences of keywords result in close map locations.

Results and Discussion

Identification of Research Trend

The network analysis of the keywords show that the research trends primarily addressed the following five clusters or aspects: (1) The restoration of wetlands plays a crucial role in mitigating climate change by regulating greenhouse gas emissions which are influenced by temperature, water-table, etc. (red cluster) (2) Methane production in wetlands, driven by the process of methanogenesis, is significantly influenced by the availability of organic matter, making wetland restoration a critical strategy for mitigating greenhouse gas emissions (green cluster) (3) Effective management of biomass in ecosystems can enhance carbon sequestration like blue carbon (blue cluster) (4) Eddy covariance measurements were used to quantify methane emissions and carbon dioxide fluxes from the wetland (yellow cluster) (5) Denitrification processes in lake sediments can influence methane emissions and nitrous oxide production, highlighting the complex interactions between nutrient cycling and greenhouse gas dynamics (pink cluster). The generated co-occurrence network map assists in exploring the most important topics regarding the restoration of lakes, wetlands, and CH_4, which were considered in our review paper.

Methane Production in Lakes

Anaerobic processes leading to the generation of CH_4 are mediated by a spectrum of microbial communities that may considerably vary in different wetlands (Grasset et al. 2021). Broadly, four groups of bacteria are recognised: (i) hydrolytic bacteria, which catabolise the organic macromolecules into smaller molecules, (ii) hydrogen-producing acetogenic bacteria that catabolise certain fatty acids and neutral end products, (iii) homoacetogenic bacteria that convert the C compounds to acetic acid and (iv) methanogenic bacteria that catabolise one-C and two-C molecules into CH_4 from a relatively small range of substrates (Welte, 2018), either by fermenting acetic acid to form CH_4 and CO_2, or by reducing CO_2 to CH_4 using hydrogen gas or use formate, methanol, methylamines, and acetate (Garcia et al., 2000). Besides bacteria, the non-CH_4 producing microbes may consist of several fungi and protozoa. Structurally, methanogens can be broadly divided into four board categories: rod, coccus, sarcina, and spiral. However, seen from the angle of CH_4 emission in lakes, in entirety, there involves three broad groups of microbes: the methanogenic anaerobes, the methanotrophic aerobes, and the methanotrophic anaerobes (Knittel & Boetius, 2009). Methane generation is the terminal step in anaerobic digestion, generally established after the depletion of other electron acceptors such as nitrate, ferric iron, and sulphate. Indeed, the input of sulphate to wetlands via pollutant deposition may have reduced CH_4 emissions (Gauci et al., 2004).

Methane Consumption in Lake

Methanotrophs consume CH_4 as their primary source of C and energy for metabolism and tend to intercept most of the available CH_4, and only the CH_4, which is not oxidized, enters the atmosphere. Methanotrophs are found in various aquatic ecosystems wherever stable sources of CH_4 are present (Topp et al., 2004). Methanotrophs are highly sensitive to variations in CH_4 concentration (Jang et al., 2011), and different methanotrophs mediate the oxidation at high and low CH_4 concentrations (Whalen et al., 1990), and the activity is enhanced at elevated concentrations. All the methanotrophs so far isolated and described need O_2 and cannot use other electron acceptors, such as nitrate, ferric, and sulfate. However, there is convincing geochemical and isotopic evidence that CH_4 is partially oxidised by anaerobic processes in anoxic marine sediments and hypersaline water (Cicerone & Oremland, 1988). In anaerobic sediment, electron acceptors other than O_2 are employed to oxidise CH_4. Important electron acceptors are the sulfate, NO_2^-/NO_3^-, and metal oxides such as Fe^{3+} and Mn^{4+}; additionally, there exists direct interspecies electron transfer (Guerrero-Cruz et al. 2021). In terrestrial freshwater-dominated ecosystems, anaerobic CH_4 oxidation probably does not occur (Zehnder & Brock, 1980). Umorin and Ermolaev (1986) established the influence of the algae (*Scenedesmus quadricauda*) on CH_4 oxidation by releasing photosynthetic oxygen. In natural ecosystems, there is usually a mutual association between microalgae and bacteria (Mouget et al., 1995); the algae provide O_2 that the methanotrophs can assimilate, while the bacteria provide CO_2 for algal growth.

Methane Emission Pathways

Methane produced in the lake may be transported in three distinct underwater pathways: ebullitive pathway, diffusive pathway, and plant-mediated pathway (Chingangbam & Khoiyangbam, 2024). The primary emission pathway for global annual lake fluxes is ebullition (23.4 Tg) followed by diffusion (14.1 Tg), ice-out and spring water-column turnover (3.1 Tg), and fall water-column turnover (1.0 Tg) (Johnson et al., 2022). Lake water is comparatively more saturated with CH_4 than the atmosphere, propelling the water-air interface diffusion, a slow but significant route of emission. In sediment with a rich labile substrate, the ebullitive pathway predominates, emitting three-fold more CH_4 than molecular diffusion (Carmichael et al., 2014). Multiple studies have endorsed ebullition as the dominant pathway of CH_4 evasion in lakes and reservoirs. Bartlett et al. (1988) attributed 49-64% of the total CH_4 flux to ebullition. In some wetlands, plant-mediated CH_4 release is a crucial route of CH_4 emission, releasing up to 70% of the overall CH_4 loss. Molecular diffusion (Joabsson et al., 1999) or convective transport processes driven by the pressure gradient between the plant and the outer environment propels CH_4 emission (Brix et al., 1992). Stomata may control CH_4 emissions in the case of cattail plants, while micropores are important in rice plants (Roura-Carol and Freeman 1999). Aerenchyma may facilitate the transport of up to 95%, enabling CH_4 to avoid oxidation owing to its morphological structure (Whiticar, 2020).

Substrate Availability

The substrate type and quality are the primary determinants of both methanogenic and methanotrophic activities. With increased organic matter, CH_4 production increases (Yagi & Minami 1990) and variation in organic matter is one of the leading causes of spatial variations in CH_4 production. However, a higher total organic content does not necessarily translate into higher CH_4 emissions as methanogens mostly consume labile forms of C, avoiding recalcitrant ones. In shallow lakes, freshly deposited organic matter provides labile and quickly mineralisable C sources (Valentine et al., 1994).

Availability of detritus and their quality, importantly having low C content or low C:N, C:P, and N:P ratio, are considered to have high detritus quality as it results in lower accumulation in sediment (Lolu et al., 2020). Two-thirds of the CH_4 is produced in nature under conditions where carbohydrates are the primary substrate derived from acetate (Conrad, 1999). Variations in the substrate quantity and quality will influence the rate at which CH_4 is produced. The lower substrate availability in deeper soil caused CH_4 production rates to decrease as soil depth increased and deeper sediments could not produce detectable CH_4 (Brooker et al., 2014). Thus, despite the presence of methanogens in deep sediments, these microbes are weak methanogens due to a lack of substrate and competition from bacteria that use other electron acceptors. Consequently, without a substrate, deeper sediments could not produce significant CH_4. Exudates supplied by roots are essential substrates for CH_4 production (Chanton et al. 1989). The availability of dissolved organic and inorganic C is vital in GHG production as it offers substrates for GHG-producing microbes such as methanogens (Upadhyay et al., 2023).

Water Temperature

Temperature is the key environmental factor controlling seasonal variation in CH_4 production and emissions from wetlands (Zhu et al., 2021). Under an unrestricted substrate supply, CH_4 generation is positively correlated with temperature (Zhao et al. 2022). Based on temperature, the microbes can be grouped into psychrophiles (0–20^{0}C), mesophiles (20–42^{0}C), and thermophiles (42–75^{0}C). Different wetland types have varying optimal temperatures for CH_4 production. A relatively small increase in sediment temperature correlates positively with CH_4 flux rates, while a negative relationship has also been described (Yang et al. 2014). Moreover, the temperature can alter the dominant methanogenic community (Lofton et al., 2014), but the size of methanogens and methanotrophs community did not change with temperature (Fuchs et al., 2016). All microbes involved in the breakdown of polymeric organic matter into intermediates and the pathway for the production of CH_4 are stimulated by temperature. The effects of increasing temperatures on CH_4 flux may vary between wetlands, attributing to variations in sediment characteristics, morphometry, and vertical mixing of the lake. Fuchs et al. (2016) showed that CH_4 production in a mesotrophic-oligotrophic lake did not alter as the temperature rose to 12 °C, representing a 7–8 °C increase relative to in situ temperatures, indicating that CH_4 oxidation must be the significant factor outweighing or even surpassing CH_4 production at rising temperatures (Shelley et al., 2015).

pH

The water and sediment pH of the lake is one of the primary factors influencing CH_4 emission because CH_4 production rates are reduced as pH values decline (Kotsyurbenko et al., 2007). Biological constraints due to pH on wetland microbial communities affect C mineralization (Goodwin & Zeikus, 1987). Methanogenesis is highly sensitive to changes in sediment pH since the methanogenic activity is typically at its optimum around neutrality or in slightly alkaline conditions (Garcia et al., 2000). The pH controls CH_4 production and positively correlates with microbial activity in soils of wetland (Valentine et al., 1994). A considerable increase in pH increased the amount of CO_2 produced, whereas a decrease in pH prevented the production of CH_4 by directly inhibiting both methanogenesis pathways, but this effect varied greatly with site and time (Dunfield et al. 1993).

Anthropogenic Percussions

Lakes, as part of their natural C cycle, embody a perpetual source of atmospheric methane. However, anthropogenic activities considerably exacerbate the emission, especially in the human intense inland ecosystems. Worldwide, freshwater lakes are used as important sources of drinking water, edible food, recreation, irrigation, and hydel-electricity (Khoiyangbam, 2021; Haroon et al., 2010) and these activities impacted the ecosystems. Human perturbation, leading to enhanced CH_4 emission from lakes, may come from three remarkable discourses: (i) degradation and alteration in structure, function, and hydrological regime of the lake ecosystem, (ii) unrestricted discharge of organic wastes into the lake, both solid and liquid, primarily in the form of raw sewage, dairy wastes, municipal garbage, etc., and (iii) excessive nutrient enrichment in lake water due to agricultural runoff and catchment erosion. An example of the first category is the increase in the CH_4 budget due to the impoundment of water for hydel power, irrigation, and drinking water supply, and the associated expansion of submergence lands. Hydro-morphological alterations may convert healthy lake ecosystems with C sequestration and climate change mitigation capabilities into C-emitting ecosystems (Morant et al., 2020). Changes in lake shapes and aerial expanse have been implicated, up to a considerable extent in regulating CH_4 ebullition and diffusion (West et al., 2016). The influx of ex-situ organic matter augments the substrate supply for methanogenesis, increasing the lake CH_4 emission budget. Globally, about 80% of wastewater is not treated (UNEP, 2021). Unrestrictive nutrient input, on the other hand, increases ecosystem productivity causing algal bloom (Khoiyangbam & Gupta, 2015). Three distinct mechanisms that may induce aquatic productivity in inland waters are increased sewage and fertilizer discharge, nutrient delivery from storms and runoff and warming of surface water. Freshwater eutrophication has a significant link with GHG emissions (Li et al., 2021) due to enhanced autochthonous organic matter production, which precludes substrate limitation. Eutrophication of lakes combined with impoundments will substantially increase CH_4 emissions over the next century, making it a hotspot for CH_4 emissions (de Mello et al., 2018). Land use patterns around the wetlands may alter the net emissions of many wetlands (Morin et al., 2014).

Climate Change and Lake CH_4 Emission

The possible impacts of ongoing climate change on natural lakes are well acknowledged (Woolway et al., 2020). Lakes are sensitive ecosystems, especially those that are shallow and small, and those in mountainous regions. A small change in the ecosystem equilibrium could destabilise the overall mechanism of their functioning. Global warming and climate change will worsen the environmental problems in lakes, demanding substantial interventions for lake restoration and sustainable management. However, many of the long-term sustainability efforts are often challenged by the uncertainty of climate change itself (Yasarer & Sturm 2016). Climatic variables such as temperature, rainfall pattern, evaporation rates, and extreme weather events affect the natural hydrological regime and strongly affect CH_4 emission (Bergström et al. 2007). Reeling under the elevated heat regime and altered meteorology, the structure and function of lakes will be disturbed, thereby flip-flopping the net emission orders of GHGs. With the unfolding of time, the emission of C from the aquatic bodies will surpass the sequestering capacity of the lake. Freshwater lakes, which produce up to 10% of the atmospheric CH_4 concentrations, are predicted to warm up over the 21st century (Bartlett & Harriss 1993). Warming waters will enhance global aquatic primary production by ~1.30× by 2100 (Downing, 2014), thereby increasing CH_4 emissions. As the climate warms, aquatic micro to macrophytes in the lake, will change. The synergistic interaction between nutrients and temperature on CH_4 production could not be ruled out (Tilman et al., 2001). Råman Vinnå et al. (2021) reported that by 2100, the CH_4 emissions from natural wetlands may increase by 50% to 80%. Further, there are worries about the possible impacts and uncertainties of climate change on CH_4 emission and, notably, the possibility of a positive feedback loop. A warmer climate and warmer lake water will increase CH_4 emissions, which in turn lead to further radiative forcing and warming.

Lake Restoration and CH_4 Emission Mitigation

In recent years, lakes have been increasingly projected to be global C storehouses and viable C sequestration options. This is because wetlands can act as sinks of GHG depending on the health and management status (Hamdan et al., 2016). Thus, lake conservation and restoration have been increasingly recognised as a crucial climate mitigation strategy and goal for the wise use of these resources. Restoration brings degraded water bodies back to their earlier state, reversing the damage and destruction. Essentially, it is vital to bring down CH_4 emissions to natural levels or switch to a net C sink. Restoration interventions employing advanced wastewater treatment, nutrient management, and pollution abatement, besides bringing social, ecological and economic gains, reduce GHG emissions (Pickard et al., 2021). Since CH_4 emission in the lake is a catchment scale process, emission mitigation strategies should entail integrated approaches stretching the entire land-water continuum. Restoration of lakes is carried out in three broad ways: (i) Minimising nutrient load, especially nitrogen and phosphorous below eutrophication levels. (ii) Water table management minimises fluctuation and enhances CH_4 emission (Harrison et al., 2017). (iii) Restricting geological nutrient input through catchment erosion and siltation. Regulating catchment nutrient losses is challenging as it envisages diverse land use and land cover, topography, and technological interventions. Environmental issues related to the discharge of untreated wastewater in lakes are pretty challenging in tropical countries with long, warm climates. In-situ restoration measures like sediment dredging are generally practised in small and shallow lakes. The restoration of peatlands using the usual flooding method is not prudent as it is associated with the release of potential nutrients and GHGs. Scrapping the peatland topsoil prior to waterlogging or slow rewetting is more encouraging. Using phosphate-binding clay particles reduces phosphate availability, restricting the proliferation of plant species like azolla and reducing substrate supply for methanogenesis. Restored wetlands may take many years, showing a gradual decrease in CH_4 emission (Waddington & Day 2007), depending on the management practices, vegetation, water table height, etc. (Herbst et al., 2011).

Conclusion

Methane emission from Lake is a complex interplay of two complementary mechanisms mediated by two distinct sets of microbes: methanogens and methanotrophs. Methanogens generate CH_4, primarily in anaerobic sediment, and methanotrophs consume the CH_4 produced in the aquatic systems. Widely documented drivers of lake CH_4 emission include macrophytes, substrates, temperature, water levels, pH, dissolved oxygen, etc. The correlation between these factors and their interphase strength needs to be revealed to predict CH_4 flux. However, quantification of CH_4 emission, taking into account all the multiple drivers, is not always straightforward due to various reasons, and results that emerge are often uncertain. First, critical gaps in scientific information still exist due to the lack of a reliable dataset, and many fundamental questions remain unanswered to establish safe conclusions. Second, the methods followed for wetland CH_4 quantification are diverse. So far, the measurements worldwide are limited to a few wetlands despite significant spatiotemporal variability within and between the various lake ecosystems. Thus, the estimates relying on a simplistic upscaling method of extrapolating average observed emission rates to a global scale rather than a process-based approach leads to significant uncertainties. Third, our understanding of CH_4 production and consumption dynamics is evolving dramatically, opening new horizons, sometimes contradicting the conventional understanding. Until recently, emission through ebullition and degassing pathways was neglected in the total GHG budgeting. Fourth, CH_4 emission is governed by a complex set of physical and biotic factors that differ between various wetlands, making it challenging to establish the dominant driver. Fifth, the unfolding of climate change and the uncertainties on its impacts on CH_4 emission drivers and their response make the understanding of CH_4 emission complex and more unpredictable.

Nevertheless, it is indisputable that wetlands are efficient C sinks due to their C sequestration capacity for a longer time scale. However, many wetlands are burdened with additional anthropogenic emissions besides their natural emission pattern. Today, countries worldwide strive to establish negative emissions of GHGs to meet international agreements such as the Paris Agreement to maintain global average temperature increment below 2^0 C, particularly the Global Methane Pledge to mitigate CH_4 emissions. Many researchers, technocrats, and policymakers are looking at ways and means to mitigate GHGs, including CH_4 emissions. Options for reducing CH_4 from lakes include restoring the degraded wetlands and rigorously protecting the intact wetlands. Restoring degraded lakes to their earlier state has been considered an essential strategy for reversing the changing climate and improving the resilience of the ecosystem to climate-related unwanted impacts. Wetland conservation and restoration has been increasingly acknowledged as a climate change mitigation strategy and a powerful remedy for reducing CH_4 emissions. Besides addressing the issue of GHG emissions, lake conservation may enhance the delivery of ecosystem services across all categories. To accomplish this purpose, it is vital to work out a precise understanding and quantification of the influence of various environmental factors on CH_4 emissions from freshwater wetlands. However, lake restoration is a long-term discourse, and it may span decades to completely re-establish an efficient C cycle, sequestration, and storage. It is always recommended that the existing intact and pristine lakes, which have net zero C emissions or act as small sinks, be conserved.

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