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Review

# Greenhouse Gases Trade-Off from Ponds: An Overview of Emission Process and Their Driving Factors

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**Abstract:** Inland water bodies (particularly ponds) emit a significant amount of greenhouse gases (GHGs), particularly methane ($CH_4$), carbon dioxide ($CO_2$), and a comparatively low amount of nitrous oxide ($N_2O$) to the atmosphere. In recent decades, ponds (<10,000 $m^2$) probably account for about 1/3rd of the global lake perimeter and are considered a hotspot of GHG emissions. High nutrients and waterlogged conditions provide an ideal environment for $CH_4$ production and emission. The rate of emissions differs according to climatic regions and is influenced by several biotic and abiotic factors, such as temperature, nutrients (C, N, & P), pH, dissolved oxygen, sediments, water depth, etc. Moreover, micro and macro planktons play a significant role in $CO_2$ and $CH_4$ emissions from ponds systems. Generally, in freshwater bodies, the produced $N_2O$ diffuses in the water and is converted into $N_2$ gas through different biological processes. There are several other factors and mechanisms which significantly affect the $CH_4$ and $CO_2$ emission rate from ponds and need a comprehensive evaluation. This study aims to develop a decisive understanding of GHG emissions mechanisms, processes, and methods of measurement from ponds. Key factors affecting the emissions rate will also be discussed. This review will be highly useful for the environmentalists, policymakers, and water resources planners and managers to take suitable mitigation measures in advance so that the climatic impact could be reduced in the future.

**Keywords:** greenhouse gases; inland water; ponds; methane; carbon dioxide; climate change



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## 1. Introduction

Inland freshwater ecosystems (e.g., ponds and lakes) cover only 3% of the Earth's surface and provide numerous ecosystem services [1]. Generally, shallow ponds (depth < 3 m) and sizes less than 2 hectares [1] provide essential resources for both aquatic and terrestrial organisms [1]. Globally, artificially constructed impoundments, particularly ponds, are mainly used for irrigation, domestic, flood control, livestock, etc., [1,2]. Kumar and Padhy [3] quoted that there are 277 million ponds with a size of less than one hectare. The water quality of inland ponds is significantly affected by anthropogenic activity in the catchment resulting in a significant amount of nutrient (nitrogen, carbon, and phosphorus) inputs and a disturbing of the biogeochemical cycling. Nutrient concentration significantly affects the water chemistry and carbon dynamics (source and/or sink) in the ponds. The chemical and biological properties [4] of the pond also influence greenhouse gas (GHG) production and emission [4–6]. Methane ($CH_4$) and carbon dioxide ($CO_2$) are the most important GHG effluxes from the ponds, but the efflux of nitrous oxide ($N_2O$) depends on the nitrogen loading. Gorsky [5] quoted that the small size pond (0.001 $km^2$) covers 8.6% of the total lentic ecosystem but accounts for 40% of $CH_4$ and 15% $CO_2$ of the total emission. The sediments in the influent to the pond, vegetation, and other dead organisms mainly contribute to organic matter and are merely available to the bacteria for degradation, resulting in a significant amount of GHG from the water–air interface [5,7]. Organic matter (OM) decomposes and results in reduced oxygen content in water, which creates an anaerobic condition in the bottom of a pond. Under an anaerobic environment, methanogenic bacteria consume the OM and lead to $CH_4$ production through the methanogenesis process [8,9]. The $CH_4$ production in the anaerobic zone of the pond is oxidized by methanotrophic bacteria in the upper aerobic zone and converted into $CO_2$ [10–12]. Mineralization of OM also emits $CO_2$ from the pond. $N_2O$ is the third important GHG, which is generally emitted from ponds under nitrogen-rich conditions through the denitrification process [13] under an anaerobic environment. The water of both urban and rural ponds has a high load of nutrients, such as nitrogen and phosphorus. A high nutrient load enhances the rate of GHG production and emission to the atmosphere. The potential of GHG production and/or emission depends on numerous biotic and abiotic factors [12–16], and their understanding is urgently required to diminish its emission potential in the future, which directly impacts future climate change and global warming. In this study, we review the methods of measurement, the process of emissions, and factors governing GHG production and emissions from small inland water bodies, such as ponds. Key factors impacting GHG emissions are also discussed. Besides, the future direction has been suggested to mitigate the medium and long-term impact on global warming.

## 2. Methodology Adopted

The study assembles and presents information and data that represents proper accountability of GHG emissions, GHG trade-off from ponds, emissions processes, and their driving factors in the freshwater ecosystem, particularly ponds. The information is gathered from reliable sources (e.g., Scopus, Science Direct, Springer, Willy, MDPI, etc.) from different research papers published in reputed journals, followed by tabulation and analysis. Besides this, there are also other data sources, such as Open Citations, CrossRef, Microsoft Academic, ResearchGate, etc. Many of them are freely available, but their validity is still questionable; therefore, they are discarded from tabulation to avoid the wrong interpretation of data. In the review, we have collected 134 pieces of literature, and the relevant studies (Nos. 82 in total) are being used for tabulation, interpretation, and analysis.

## 3. Ponds in the Landscape

Ponds are small, heterotrophic water bodies (representing 30% of surface standing water on Earth) that make a significant contribution in global metabolic active aquatic sites, as well as global ecological systems with the high intensity of carbon processing. The small size of the ponds and their intense metabolic activities have high dynamics compared to the large standing surface water bodies due to the high inflow rate of nutrients, generation of the GHG, succession rate, and tradeoffs of the toxic substances, such as metals [3]. Ponds can serve as sustainable units to address the issue at global levels, such as water management, especially groundwater recharge, retention of the nutrients, aquatic floral and faunal biodiversity conservation, and sequestration of the carbon through phytoplanktons. However, due to changing environmental scenarios, as well as the pace of modern life, ponds are also vulnerable and need special attention to address climate change, flood relief, biodiversity conservation, and pollution alleviation. Ponds are comparatively economic, easily constructed, manageable, and available in the proximity of almost every rural settlement and can be protected easily with local participation. Ponds need significant support to achieve the United Nations Sustainable Development Goals

(UN-SDGs), as sustainable water management of the pond can support the climate change impact abetment, recreations works, livelihood protection, irrigation support, livestock watering, flood management, restrict the agricultural and settlement related pollution, microclimate regulation at the local and regional scale, and recharge groundwater.

## 4. Mechanism of Greenhouse Gas Emission from Ponds

### *4.1. Methane Emission from Ponds*

Diffusion, ebullition, and plant-mediate transportation are three major pathways (Figure 1) of $CH_4$ emission in the ponds [14–16]. Gorky et al. [5] reported that the contribution of $CH_4$, $CO_2$, and $N_2O$ were 94%, ≈6%, and <1%, respectively, to the total GHG emissions from small ponds. In general, $CH_4$ significantly contribute to total GHG emissions from inland water bodies. Ebullition and diffusion are dominant pathway (Figure 1) processes through which $CH_4$ emits from pond water to the atmosphere [4,5,16]. Depending on water chemistry and environmental variables, ebullition contribution may range from 50 to 90% of total $CH_4$ fluxes [12,14–16]. The percentage contribution of the diffusion process to total $CH_4$ emissions from inland water varies from 10 to 25%, and it is mainly governed by both abiotic and biotic factors [12,14–16]. Selvam [15] estimated the $CH_4$ emissions from 45 different inland water bodies of India (see Section 4.3.) and reported that $CH_4$ emissions from the pond through a diffusion pathway (16.76% of total $CH_4$ fluxes) was 3.1 mmol $m^{-2}$ $d^{-1}$, while the total $CH_4$ flux was 18.5 mmol $m^{-2}$ $d^{-1}$. Constructed freshwater ponds are utilized for fish farming and other beneficial activities globally [17–19]. Yuan et al. [19] investigated the $CH_4$ emission pathway from freshwater aquaculture ponds and observed that ebullition contributes from 79.1 to 83.5% of the total $CH_4$ flux, which indicates that it is the main $CH_4$ emission pathway in freshwater aquaculture ponds. Similar findings were also reported by Zhao et al. [17]. Zhao et al. [17] measured $CH_4$ emissions from freshwater constructed aquaculture ponds and found that the ebullition $CH_4$ emissions account for 70% of the total $CH_4$ emissions. Yang et al. [18] found a slightly higher (90% of the total $CH_4$ flux) contribution of the ebullition pathway to total emissions.

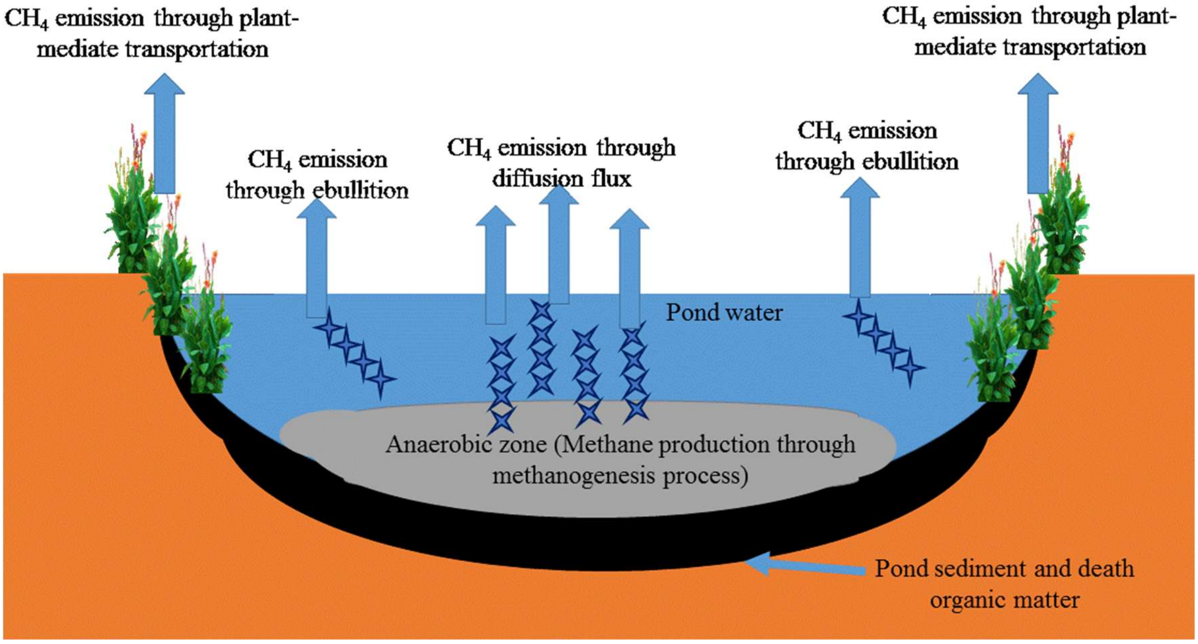


**Figure 1.** Pathway of methane emissions from a pond.

Grinham et al. [16] investigated the $CH_4$ emissions from the pond and other small inland water bodies of Queensland, Australia, and found that ebullition is the dominant pathway of $CH_4$ emissions. In one study, Holgerson and Raymond [20] investigated the contribution of $CH_4$ and $CO_2$ emissions from very small ponds (0.001 $km^2$) and found that diffusive pathways involve 40.6% of the total $CH_4$ flux. Ortega et al. [21] estimated the $CH_4$ emissions from freshwater inland water bodies of the city of Berlin, Germany, and observed that ponds (2.11 $km^2$) emit 300 mg $CH_4$ $m^{-2}$ $day^{-1}$ (71.43% of the total $CH_4$ flux) and 120 mg $CH_4$ $m^{-2}$ $day^{-1}$ (28.57% of the total $CH_4$ flux) through ebullition and the diffusion pathway, respectively [21]. The flux of $CH_4$ through ebullition increased with nutrient enrichment of the pond and lakes, while $CH_4$ emissions through the diffusion pathway did not show a positive correlation with nutrient enrichment of the water [22]. Nutrient enrichment in the pond resulted in phytoplankton blooms on the surface, resulting in reduced sunlight penetration, leading to the extinction of the submerged plant and reduced dissolved oxygen. This led to an enhanced population of methanogens, which increased the $CH_4$ emissions [22]. The abundance of submerged macrophytes significantly affected the $CH_4$ emission pathways. Ebullition and diffusion have negative and positive correlations, respectively, with submerged macrophytes [22].

### 4.2. Carbon Dioxide Emissions from Ponds

Generally, there are two direct (soil respiration processes and degradation of dissolved OM) and one indirect ($CH_4$ oxidation by methanotrophs) pathways or processes involved in $CO_2$ emissions from water bodies [23,24]. Firstly, the release of $CO_2$ from the soil respiration increases the total $CO_2$ in the water and the excess $CO_2$ above the saturation limit is released into the atmosphere. Secondly, aquatic microbes actively perform in-situ degradation of dissolved OM in the water bodies and release $CO_2$ gas to the atmosphere in this process. Thirdly, $CH_4$ gas is produced in the anaerobic zone and this produced $CH_4$ is trapped by methanotrophic bacteria in the aerobic zone. The trapped $CH_4$ is utilized by methanotrophic bacteria as the sole source of carbon (especially labile organic carbon) and finally converted to $CO_2$, which is emitted to the atmosphere [23–25].

### 4.3. Nitrous Oxide Emissions from Ponds

Nitrous oxide is an ozone-depleting GHG, and it is long-lived and considered as having a higher global warming potential compared to $CO_2$ and $CH_4$ [13,26]. Therefore, environmentalists pay more attention to its quantification in this modern era of urbanization and industrialization. Nitrous oxide concentration has significantly increased after industrialization, and its combat is crucially required to fight enhanced global warming. The contribution of the anthropogenic flux of $N_2O$ to the atmosphere from ponds, streams, rivers, etc. is negligible to the total GHG emissions [22]. Xiao et al. [27] investigated the $N_2O$ emissions from different inland water bodies of the agricultural watershed and reported that pond systems emit 19 nmol $L^{-1}$ annually. Nitrogen-based fertilizer runoff reaching nearby ponds, streams, and rivers is the main source of anthropogenic $N_2O$ emissions [27]. The $N_2O$ produced in freshwater ponds generally moves downwards and is consumed in benthic sediment, and, therefore, ponds are considered a weak source of $N_2O$ emissions [19]. The GHG efflux, especially $CH_4$, $CO_2$, and $N_2O$ from the ponds located in different parts of the world, is listed in Table 1 and further the detailed sampling methods has been discussed in the Section 5 below.

**Table 1.** Methane, carbon dioxide, and nitrous oxide flux ranges reported globally in different studies.

| Reference | Location Detail | Sampling Methodology | Methane | Carbon Dioxide | Nitrous Oxide | Remarks |
|---|---|---|---|---|---|---|
| Selvam et al. [15] | Different water bodies of Tamil Nadu, Andhra Pradesh, and Kerala | Floating chamber | 0.1–52.1 mmol $m^{-2}$ $day^{-1}$ | −28.2 to 262.4 mmol $m^{-2}$ $day^{-1}$ | - | In this study, 45 different water bodies, such as ponds, open wells, lakes, and channels were studied |
| Audet et al. [28] | Silkeborg, Denmark | Headspace sampling | 44 μg $L^{-1}$ | 1938 μg $L^{-1}$ | 0.8 μg $L^{-1}$ | In this study, authors reported the mean concentration of GHG emissions from urban ponds |
| Peacock et al. [29] | Uppsala, Sweden | Floating chamber | 0.1–44.3 g $CH_4$ $m^{-2}$ $year^{-1}$ | −36 to 4421 g $CO_2$ $m^{-2}$ $year^{-1}$ | - | Small constructed ponds and ditches |
| Peacock et al. [30] | Uppsala, Sweden | Headspace method | 0.4–174 mg $CH_4$ $m^{-2}$ $year^{-1}$ | −187 to 3449 mg $CH_4$ $m^{-2}$ $year^{-1}$ | - | Small urban ponds |
| Pickard et al. [31] | Bengaluru, India | Headspace sampling | 0.33–3413 ton $CH_4$-C evasion $year^{-1}$ | 24–5711 $CO_2$-C evasion tone $year^{-1}$ | - | Inland polluted urban lakes near industrial areas |
| Webb et al. [32] | Saskatchewan, Canada | Headspace method | 0.14–92 mmol $m^{-2}$ $day^{-1}$ | 21–466 mmol $m^{-2}$ $d^{-1}$ | - | Small agricultural farm reservoir |
| Natchimthu et al. [33] | Linkoping University, Sweden | Floating chamber | 3.3–15.1 mmol $m^{-2}$ $day^{-1}$ | −9.8 to 16.0 mmol $m^{-2}$ $day^{-1}$ | - | Freshwater shallow pond |
| Singh et al. [34] | Ujjain City, India | Floating chamber | - | - | 0.00–0.51 mg $m^{-2}$ $day^{-1}$ | Urban pond receiving domestic and agricultural runoff |
| Wang et al. [35] | Beijing, China | Headspace sampling | 0.08–8.3 mmol $m^{-2}$ $day^{-1}$ | −24.2 to 37.9 mmol $m^{-2}$ $day^{-1}$ | - | Urban inland water bodies such as lakes |
| Schrier-Uijl et al. [36] | Different peats drainage ditches of Netherlands | Floating method | 33.7 mg $m^{-2}$ $h^{-1}$ | 129.1 mg $m^{-2}$ $h^{-1}$ | - | In this study, mean $CH_4$ and $CO_2$ emissions were reported from shallow freshwater bodies |
| Ortega et al. [21] | Berlin, Germany | Floating chamber | 385 Mg $CH_4$ $year^{-1}$ | - | - | Emissions from urban ponds |
| Grinham et al. [16] | Queensland, Australia | Floating chamber | 1.6 Mt $CO_2$ eq. year-1 | - | - | Small artificial ponds, lakes, etc., were investigated |
| Wik et al. [37] | 733 lakes and ponds of Northern regional | - | 1.0 Tg $CH_4$ $year^{-1}$ | - | - | Findings for Beaver ponds |
| | | | 3.1 Tg $CH_4$ $year^{-1}$ | - | - | Results of peatland ponds |
| | | | 16.5 Tg $CH_4$ $year^{-1}$ | - | - | Total $CH_4$ emissions from Beaver ponds, Peatland ponds, Glacial/post-glacial lakes, and Thermokarst bodies |
| Zhao et al. [38] | Anhui Province, China | Eddy covariance | 1.05–1.66 μg $m^{-2}$ $s^{-1}$ | 0.011–0.024 mg $m^{-2}$ $s^{-1}$ | - | Two small fish ponds |

## 5. Methods for Greenhouse Gas Emissions Measurement from Ponds

In general, measurement of the GHG emissions from the pond is achieved through frequently used methods called "floating chambers, headspace, and funnels". Eddy covariance (EC) towers are used rarely by the scientific fraternity because of the high cost and the need for a technician for handing and installing the EC tower (see details below in sub-sections) [17,39,40]. These techniques have their advantages and limitations for measuring the spatial and temporal coverage, along with the accuracy to capture the GHG flux (diffusive and ebullition). GHG measurements from small size ponds using the EC are generally not recommended due to difficulty in the determination of the accurate fetch and economics.

### 5.1. Floating Chamber Method

The floating chamber method is widely used for the GHG measurement from ponds and other water bodies (Table 1). It should be constructed in different sizes and shapes (depending on the lake size and requirements) by using chemically inert materials, such as polyacrylic sheets etc. The chamber should be open at one end and attached with the float (floating sheet) in such a way that the chamber can be sufficiently submerged in the water to avoid air penetration [17,41]. The floating sheet makes it an enclosed system. The floating chamber should be connected with a sampling pump and Tedlar bag via a three-way stopcock. The sampling is done at different time intervals based on the temporal trends of GHG emissions from the pond. The effective mixing of the air before collecting the sample should be ensured. The collected samples should be transported to the laboratory in ice-cool bags and analyzed immediately through gas chromatography (GC) using desired detectors (FID, TCD).

### 5.2. Headspace Sampling

GHG partial pressure measurements can also be achieved with the headspace gas chromatography (HS-GC) procedure. The water samples should be collected into tight containers, such as glass vials/borosilicate glass bottles, to avoid the change of methane adsorption on the container walls [42,43]. The precaution to restrict the gas exchange should be taken at the time of the water sampling through water samplers. In this procedure, the headspace (gas phase) lies above the liquid phase (sample phase) containing the dissolved greenhouse gases. The glass vials are to be sealed after the introduction of the liquid phase into them. The diffusion of the volatile component continues till the headspace achieves equilibrium [43]. The gas sample is collected from the headspace and analyzed by gas chromatography. The septum is baked for 2–3 h at 60 °C to remove traces of GHG-producing chemicals. The precaution related to the calculation of the headspace volume calculation should be taken by using a minimum of 30 bottles, and the average mean should be used. A preservative such as KCl should be used to restrict the biological activity between sampling and analysis, especially in the case of $CO_2$. The water temperature and atmospheric pressure should be recorded and used in the calculations for the partitioning of gas between the water and gas phases.

### 5.3. Bubbles Trapped Using Inverted Funnels

Bubble fluxes (ebullition) from the pond can be measured through inverted funnels coupled to gas collectors initially filled with water. Bubble fluxes mainly occur in shallow ponds. The shallowness part of the ponds bears the low hydrostatic pressure, and dissolution of the GHG is not possible in the interstitial water. The bubble collectors should be installed below the wind–wave influence. This method can be used to know the integrated flux over different periods. This technique is comparatively cheap and easy to perform for the GHG estimation from the ponds. The size of the inverted funnel should be decided based on the bubble emission [44,45]. The funnel should be submerged, and all the pre-existed air needs to be removed before the commencement of sampling. Before performing GHG sampling and analysis through this method, it should be confirmed that the water flow is zero and the bottom slope of the pond is <20 degrees. Both of these conditions ensure the stability of the sampling system for a long duration and also minimize procedural errors. The sampling interval should be less than 20 h to avoid diffusion of the GHG.

## 6. Factors Affecting Greenhouse Gas Emissions from Ponds

GHG emissions from ponds are affected by several factors, such as water quality [46], temperature [47], water depth, eutrophication, micro-macro flora-fauna, etc. [48,49] (Table 2). Some of the important factors which govern the GHG emissions from the pond are discussed briefly in this section.

**Table 2.** Impact of different factors on greenhouse flux from water bodies.

| Factors | Correlation with $CH_4$ Flux (References) | Correlation with $CO_2$ Flux (References) | Correlation with $N_2O$ Flux (References) |
|---|---|---|---|
| Water temperature | Increased exponentially up to certain limit [22,28,29,33,35,47,48,50,51] | Positive [28,29,35] | Positive [28,50,52] |
| | No correlation [12,53] | No correlation [47,48] | - |
| | - | Negative [33] | Negative [54] |
| Nitrate concentration | No impact [51] | Positive [55] | Positive [51,55,56] |
| | Negative [28,57] | - | - |
| Dissolved organic matter (DOM) | Positive [5,30,35,40,56,58] | Positive [5,53,58] | Positive correlation [5,59] |
| Water pH | - | Positive [5,60] | Positive [59] |
| | Non-significant correlation [40,46] | - | Non-clear correlation [52] |
| | - | Negative [4,5,30,40,46] | Negative [56] |
| Dissolved oxygen (DO) | - | - | Positive [46,59] |
| | No correlation [46] | - | - |
| | Negative [28,29,40,56] | Negative [40,46] | Negative [56] |
| Surface area of pond | Negative [5,29] | - | Positive [61] |
| Total nitrogen (TN) | - | Positive [46] | Positive [52,56] |
| Total phosphorus (TP) | Positive [29,30,46,57] | Positive [46] | Positive [46] |
| Sulphate | Negative [12,28] | - | - |
| Eutrophication | Enhanced $CH_4$ flux [22,49,62,63] | Positive [62] | - |
| | - | Negative [63] | Negative [62] |

### *6.1. Effect of Water pH on GHG Emissions*

#### 6.1.1. Methane

Hao et al. [46] reported that water pH has a non-significant correlation with $CH_4$ emissions from inland water bodies, such as ponds (Table 2). A similar finding was also reported by Yang et al. [40] in Northern Taiwan (Table 2). Methane-producing bacteria are pH sensitive, and they produce $CH_4$ in a narrow range (pH, 6–8). The pH of some of the ponds around the globe at different geographical locations has been summarized in Table 3. Based on Table 3, it can be concluded that the pH of freshwater bodies, especially inland ponds, was within or around this narrow pH range (from 6–8) and, therefore, the pH of pond water was not having any significant correlation with $CH_4$ emissions.

**Table 3.** pH range of the water bodies at the global level.

| Location of the Study/Reference | Range of Water pH | Remarks |
| --- | --- | --- |
| Uttar Pradesh, India [64] | 7.2–8.2 | Out of 12 studied ponds, only at 1 location, the pond water pH was 9.2 (No GHG) |
| Chhattisgarh, India [65] | 6.93–7.55 | The authors investigated the water quality of 10 ponds (No GHG) |
| Bihar, India [66] | 6.35–7.57 | Pond water quality of two districts was investigated in this study. (No GHG) |
| Tamil Nadu, India [67] | 7.25–8.85 | Out of a total of 17 investigated temple ponds, only 2 ponds (pH 9.07 and 8.42) had a pH above 8. (No GHG) |
| West Bengal, India [68] | 7.5–7.9 | In this study, water quality of both rural and urban ponds was conducted. (No GHG) |
| Balochistan province, Pakistan [69] | 7.11–7.96 | This study conducted the assessment of the water quality of fish farming ponds of four districts of Balochistan province, Pakistan. (No GHG) |
| Dhrabi Watershed, Pakistan [70] | 7.2 | The study was conducted in Dhrabi reservoir of Pakistan. |
| Ontario, Canada [71] | 5.77–7.74 | In this study, water quality of 51 natural ponds was investigated. |
| National Capital Region of Canada, Canada [72] | 5.77–9.23 | In this study, water quality of 10 natural ponds and 40 stormwater constructed ponds was investigated. The pH of all-natural ponds was below 8 while higher pH was observed in stormwater constructed ponds. |
| Patuakhali district, coastal watershed, Bangladesh [73] | 7.6–7.9 | Water quality of coastal ponds during pre-monsoon, monsoon, and post-monsoon was reported. |
| Silkeborg, Denmark [28] | 7.5–8.0 | The water quality of four urban ponds was reported in this study. |

#### 6.1.2. Carbon Dioxide

Carbon dioxide emissions from water are usually low as it is dissolved in the water and produces carbonic acid [74]. The pH of the pond water has both positive and negative correlations with $CO_2$ flux from the pond (Table 2). Peacock et al. [29] reported a negative correlation between water pH and $CO_2$ emissions from pond water (Table 2). Similarly, a negative correlation between pH and $CO_2$ emissions is also reported by Hao et al. [46] in China. Hao et al. [46] investigated the GHG emissions from 18 field campaigns, including ponds, lakes, wastewater, swamps, etc., and found the $CO_2$ from ponds ranged from 0.02 to 4.81 mol $m^{-2}$ $d^{-1}$ and had a negative correlation ($r = -0.804$, $p < 0.01$) with water pH.

#### 6.1.3. Nitrous Oxide

Hao et al. [46] reported that water pH has no correlation with $N_2O$ emissions from the inland water bodies such as ponds (Table 2). Singh et al. [52] investigated the $N_2O$ emissions from urban pond water and reported that the correlation between the water pH and $N_2O$ flux is very complex. Generally, when water pH decreases, $N_2O$ emissions from water bodies increase, and denitrification plays an important role in this flux [52]. The highest $N_2O$ flux through denitrification is in the narrow range of pH 7–8 [13,52]. At a higher water pH, microbial activities are suppressed, which retards the denitrification and nitrification processes, resulting in lower $N_2O$ emissions [56,75].

*6.2. Effect of Temperature on GHG*

6.2.1. Methane

In the pond ecosystem, sediment and water temperature significantly affect the $CH_4$ emissions [12,48,50]. DelSontro et al. [48] observed that the rate of $CH_4$ diffusion from ponds shows a positive correlation on increasing sediment temperature from 10 to 25°C. Peacock et al. [29] conducted an extensive study on GHG emissions from small artificial water bodies such as ponds and found that the $CH_4$ emissions were highest at higher temperatures (summer season) while the rate of $CH_4$ emissions was lower during winter (Table 2). Peacock et al. [29] observed that the mean annual $CH_4$ emissions from water bodies ranged from 0.1 to 44.3 g $CH_4$ $m^{-2}$ $year^{-1}$.

Boron et al. [12] reported that $CH_4$ fluxes increased exponentially with temperature. The rate of $CH_4$ emissions through ebullition increased by 11% on a 1°C rise in water temperature, while with a 10 °C rise in temperature, $CH_4$ emissions enhanced up to 2.8 times through the ebullition process [35]. Organic matter present in the soil is the substrate for methanogenic bacteria. The water temperature increase enhanced the decomposition rate of sediment OM which is an oxygen demanding process. Decomposition of OM depletes water oxygen which results in an anaerobic environment and favors $CH_4$ production through methanogenesis. The rate of $CH_4$ emissions through the ebullition process increased exponentially over 17°C, and the water temperature had a non-significant correlation on $CH_4$ emissions through the diffusion pathway [35]. However, Hao et al. [46] found no significant correlation between the $CH_4$ emissions and water temperature. Hao et al. [46] found that the $CH_4$ emissions concentrations decrease with a water temperature increase due to the enhanced activity of methane-oxidizing bacteria (MOB). At a higher temperature, MOB consume more $CH_4$ and convert it into $CO_2$, which results in a lower emission of $CH_4$ [46].

6.2.2. Carbon Dioxide

There are controversial findings regarding the relationship between $CO_2$ emissions from ponds and temperature (Table 2). The water temperature of pond ecosystems does not show any correlation with $CO_2$ diffusion [48]. DelSontro et al. [48] found that the $CO_2$ diffusion did not change with the increase in sediment temperature from 10 to 25 °C. Audet et al. [28] reported seven major $CO_2$ emission influencing factors such as vegetation, pH, sulfate, DO, ammonium, temperature, and water temperature. The water temperature influences the contribution to around 7%, in comparison with the total 100% influence.

6.2.3. Nitrous Oxide

Generally, pond freshwater bodies emit negligible or no $N_2O$, as a majority of $N_2O$ produced is diffused back and converted to $N_2$ gas through biological processes. Water temperature has a strong and positive correlation with the denitrification pathway which finally enhances the $N_2O$ flux [50,51]. Higher water temperature enhances the oxygen demanding metabolic pathways, which depletes the DO of the water and creates an anaerobic environment, resulting in a higher denitrification process [13,50]. In one incubation study, Samarkin et al. [76] found that the rate of $N_2O$ production positively correlated with temperature. The $N_2O$ production starts at −20 °C and exponentially increases with temperature [76]. However, contradictory findings were also reported by Paudel et al. [55]. Paudel et al. observed that the $N_2O$ emissions from freshwater aquaculture systems significantly decreased with increased water temperature.

*6.3. Effect of Nutrients Concentration on GHG Emissions*

6.3.1. Methane

Nitrate and phosphate in the water have a negative and positive correlation with $CH_4$ emissions from pond water, respectively (Table 2). Nitrate acts as an electrons acceptor and inhibitor for the methanogenesis processes and, therefore, results in lower $CH_4$ production [57]. Phosphate in water causes eutrophication which may enhance more liable organic matter in the system and the generation of $CH_4$ by methanogenic bacteria [4,28,57].

The nutrient load, such as nitrate, total organic carbon, TN, etc., has a significant positive correlation with $CH_4$ production in small ponds (Table 2). Organic matter (OM) has a positive correlation with $CH_4$ production and emission from ponds. In general, OM decomposes in the anaerobic zone of ponds and significantly contributes to $CH_4$ emissions (Table 2). Recently, Gorsky et al. [5] investigated the $CH_4$, $N_2O$, and $CO_2$ emissions from 15 stormwater ponds of Virginia, USA, and found that OM has a positive correlation with $CH_4$ emissions. $CH_4$ emissions contribute 94% of the total GHG, and the mean $CH_4$ flux was 15.1 mg $m^{-2}$ $h^{-1}$. Organic carbon contributes roughly 6% and 20% to total C emissions from ponds and reservoirs [47,77]. Peacock et al. [30] observed that the rate of $CH_4$ emissions from the urban pond was positively correlated with the total organic carbon and total phosphorus. Water sulfate also has a negative correlation with $CH_4$ production and emission [12]. Higher sulfate concentration in water enhances the population of sulfate reduction bacteria [78], and these sulfate reducing bacteria compete with methanogenic bacteria for OM. The higher sulfate reducing bacteria reduced $CH_4$ production by suppressing methanogenic activity as they both utilized the same carbon source as labile organic carbon [7].

#### 6.3.2. Carbon Dioxide

Carbon dioxide flux from the freshwater system is a biological process and has a positive correlation with nitrogen [13]. The high nitrogen in water enhances the algal growth, and this high algal biomass settles down in the benthic region of the pond and degrades through the biological processes, resulting in emissions from the air–water surface [32]. The high nitrogen favors the nitrification and denitrification process, as a result of which $CO_2$ is released into the atmosphere [32]. Constructed wetlands are widely used to reduce the nutrient load from the water stream [9]. Badiou et al. [79] investigated the GHG emissions from both untreated and constructed wetlands treated stormwater. Their results reveal that total cumulative $CO_2$ flux from untreated and constructed wetland treated water was 12,631 g $ha^{-1}$ $day^{-1}$ and 6447 g $ha^{-1}$ $day^{-1}$ [79]. The nutrient load, such as total nitrogen, phosphorus, nitrate, etc., is lower in treated water, and this supports that the $CO_2$ emission from water is generally positively correlated with the nutrient load.

#### 6.3.3. Nitrous Oxide

Nitrous oxide emissions from freshwater have a positive correlation with the inorganic N components (Table 2). $N_2O$ in freshwater is mainly produced through the denitrification process, and N components, such as nitrate ($NO_3^-$-N) and ammonium ($NH_4^+$-N), are the substrate for this complex process [56,59]. The emission of $N_2O$ from pond water has a positive correlation with nitrate and sulfate [50]. Nitrate present in water acts as a primary raw source for the denitrification pathway and emits $N_2O$ to the atmosphere [9,50,80]. Audet et al. [28] quoted that higher sulfate produced sulfide in water, and this sulfide inhibited the conversion of $N_2O$ to $N_2$ gas, and, therefore, higher $N_2O$ is emitted under more water sulfate concentration.

### *6.4. Effect of Eutrophication on $CH_4$, $CO_2$, and $N_2O$ Emission*

Eutrophication results in the depletion of the DO concentration in pond water, and eutrophication processes have a positive correlation with $CH_4$ and $CO_2$ emissions [49,57,62]. Eutrophication enhanced the labile organic carbon (LOC) in the pond ecosystem, and this LOC is rapidly consumed by methanogenesis bacteria in anaerobic conditions, liberating $CH_4$ as a by-product GHG gas. Beaulieu et al. [49] reported in a recent simulation that, over the next century, eutrophication may enhance from 30 to 90% $CH_4$ emissions from impoundments bodies. Freshwater eutrophication results in high biomass production [81] and is decomposed under low DO. After decomposition, this biomass is mineralized under a reduced environment and liberates $CH_4$ and $CO_2$ as a by-product [62].

## 7. Conclusions

Inland freshwater bodies, such as ponds, ditches, etc., are either less monitored or completely ignored for their role in greenhouse gas (GHG) emissions to the atmosphere. Freshwater ponds and urban ponds significantly emit methane ($CH_4$) and carbon dioxide ($CO_2$). Water temperature and dissolved organic matter have a positive correlation with $CH_4$, $CO_2$, and $N_2O$ emissions from the pond. Water pH ranging from 6.5 to 8.5 is considered most favorable for the biological activity and the production and emission of $CO_2$ and $N_2O$ in the atmosphere. Eutrophication increases the biomass of the pond, which later settles down at the benthic region and degradation of the same under an anaerobic environment significantly enhances $CH_4$ emissions. Further, water, phosphorus, and nitrogen have a positive correlation with $CO_2$ and $N_2O$ production. Dissolved oxygen concentration (DO) has a negative correlation with $CH_4$ and $CO_2$ emissions, while contradictory findings were reported for $N_2O$ emissions. The nutrient load and DO are two key factors affecting the GHG emissions from the pond system. Therefore, the appropriate design of constructed wetlands could reduce nutrient load and enhanced DO in the ponds and have a significant prospect for the mitigation of GHG in pond systems and other inland water bodies.

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