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Greenhouse Gas Emission from Inland Open Water Bodies and Their Estimation Process—An Emerging Issue in the Era of Climate Change

Thangjam Nirupada Chanu*, Subir Kumar Nag, Satish Kumar Koushlesh, Manoharmayum Shaya Devi, Basanta Kumar Das

ICAR-Central Inland Fisheries Research Institute (CIFRI), Barrackpore, India
Email: *nirupada@gmail.com

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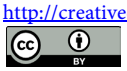

Abstract

The persistent rise in concentrations of greenhouse gases (GHGs) in the earth's atmosphere is responsible for global warming and climate change. Besides the known source of GHGs emissions like energy, industry, and agriculture, intrinsic emissions from natural inland water bodies like wetland, rivers, reservoirs, estuaries, etc. have also been identified as other hotspots of GHGs emission and gaining the attention of the scientific communities in recent times. Inland fisheries in India are threatened by climate changes such as a change in temperature, precipitation, droughts, storm, sea-level rise, saltwater intrusion, floods that affect mostly the production, productivity and ultimately affect the fishers' livelihood. There are, however, different mitigation and adaptation strategies to cope with the effects of climate change. Carbon sequestration and other related management interventions are one of the options available for minimizing GHGs emissions from inland open waters, particularly the wetlands and coastal mangroves which are well known worldwide for their significant role in the storage of carbon. Assessment of C efflux from exposed sediments in dry streams, reservoirs, lakes, rivers, and ponds into the atmosphere can be considered imperative for a better understanding of their role as a C-sink or as a C-source to the atmosphere.

Keywords

Greenhouse Gas, Inland Open Water, Global Warming Potential, Carbon-Dioxide, Methane, Nitrous Oxide

1. Introduction

Unfavorable and irreversible climatic aberration known to us as climate change

is an issue that has marred the possibility of sustainable existence of life forms and healthy biological processes that governs the well-being of the present and the future generations of human being on earth. The effects of climate change are manifested as a steady rise in average sea surface temperature, relatively more frequent extreme weather events, rising sea level, and a range of other impacts. Increasingly convincing scientific evidence is being put forth and validated by various researchers across the world which depicts the existing warming trend on our earth climatic systems and more obviously from record rise in global mean annual sea surface and air temperature driving rapid melting of icy glaciers thus rising mean sea level [1]. The global mean annual sea level rose during the year 2005 to 2015 at the rate of 3.58 ± 0.25 mmyr^{-1} [2] [3]. Further, most of the simulation studies also suggested that the change in the mean global annual surface temperature between the period 1850 and the end of the 21st century is likely to exceed 1.5˚C, and temperature rise of 2˚C is anticipated to be dangerous for sustainability of life forms. It is still uncertain how great climate change would impact the earth. Some major impacts could be shortages of freshwater, alteration in food production ability, loss of habitats for various plants/animals, driving unusual distributional trends in wildlife populations into newer habitats, loss of biodiversity, extinction of species, etc.

It is suggested that the persistent rise in concentrations of greenhouse gases (GHGs) in the earth's atmosphere is responsible for global warming and the climate change crisis. The intensification of non-climate friendly activities in the past century aided by fossil fuel burning and emission from industries, urban and vehicular traffic globally has been identified as one of the most significant drivers to the problem of rising GHGs emissions. In addition, intrinsic emissions from natural habitats like wetlands, rivers, and reservoirs have also been identified and gaining the attention of the scientific communities in recent times. There are several scientific studies [4]-[9] on the role of reservoirs in global GHGs emissions particularly more so in the tropical and sub-tropical region.

1.1. Greenhouse Gases

The gaseous constituents of the atmosphere owing to contributions from both natural and anthropogenic sources, absorbing and emitting radiation at certain wavelengths within the infrared spectrum via Earth's surface, atmosphere, and clouds are called greenhouse gases (GHGs). Primarily these GHGs in the atmosphere consist of water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3). GHGs possessed the property to absorb and release infrared radiation, which facilitates the trapping of the sun's warmth leading to the "greenhouse effect" [10]. Apart from these, there are several man-made GHGs like, halocarbons, and chlorine or bromine-containing substances which are dealt under the Montreal Protocol. The Kyoto Protocol deals with the greenhouse gases like CO_2, N_2O, CH_4, sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) (As per the definition of

WG III, IPCC).

According to global warming potentials (GWP), the most dangerous GHGs present in the atmosphere consisted of CO_2, CH_4, N_2O, water vapor, and anthropogenically produced gases like hydrofluorocarbons and perfluorocarbons. The concentrations of primary GHGs, their lifetime, sources, and GWP are presented in Table 1. Among other GHGs, CO_2 gained the most attention in popular media due to the contribution from anthropogenic activities. But, according to GWP, CH_4 has 25 times more GWP per molecule and N_2O is about 300 more potent in GWP per molecule than CO_2 [1] [11]. In 2017, the global concentrations in earth's atmosphere of these GHGs *i.e.*, CO_2, CH_4, and N_2O were approximately recorded to be 408.0 ± 0.1 ppm, 1869 ± 2 ppb, and 331.0 ± 0.1 ppb respectively, which show an increase of approximately 45% for CO_2, 160% for CH_4 and 22.63% for N_2O since 1750 [3] [12].

1.2. Need for Assessment of the Emission of GHGs in Inland Open Waters

Human activity modifies the dynamics of CO_2, CH_4, and N_2O in the aquatic environment. Inland freshwater systems are sources of greenhouse gases (GHGs) to the atmosphere and as such, their importance in global GHG budgets is increasingly recognized. Outgassing of CO_2 and CH_4 from these systems account for an estimated 3.9 $PgCyr^{-1}$ of the 5.1 $PgCyr^{-1}$ exported globally from the terrestrial environment to freshwaters [14], although considerable uncertainty about the accuracy of these estimated fluxes remains.

Inputs from agriculture, wastewater discharge from various industries into inland water, amongst other sources may amplify GHG emissions. However, we still lack a crucial "bottom up" understanding developed from field measurements of

Table 1. Primary GHGs concentrations, its lifetime, sources, and its global warming potential [13].

GHGs	Pre-industrial concentrations (ppmv*)	Recent concentrations in 2018 (ppmv*)	Atmospheric lifetime (years)	Main human activity sources	GWP**
Carbon dioxide (CO_2)	280	407.8	Variable	Fossil fuels, cement production, land-use change	1
Methane (CH_4)	0.715	1.86	12	Fossil fuels, rice field, waste disposal, livestock	21
Nitrous (N_2O)	0.27	0.3311	114	Fertilizers, combustion, industrial processes	310
Hydrofluorocarbons (CHF_3)	0	0.05	270	Electronic refrigerants	11,700
Perfluoromethane (CF_4)	0	0.05	50,000	Aluminum production	6500
Perfluoroethane (C_2F_6)	0	0.05	10,000	Aluminum production	9200
Sulfur-hexafluoride (SF_6)	0	0.05	3200	Dielectric fluid	23,900

ppmv* = parts per million by volume, GWP = 100-year global warming potential.

the magnitude of these emissions, and how they compare on a catchment scale to emissions from non-anthropogenic GHG sources.

Due to anthropogenic activities and global warming, the health of wetlands is degrading resulting in the release of more GHGs than the amount absorbed. Many studies have proven that lakes and other inland waters are significant global emitters of CO_2, CH_4, and N_2O [5] [15] [16] [17]. Dams are recognized as the single largest anthropogenic source of methane emission (National Institute of Space Research, Brazil). Methane released from dams contributed 23% of cumulative methane emissions owing to anthropogenic activities. Thus, reservoirs are considered to be a significant source of greenhouse gases emission (GHGs) into the atmosphere [5]. Reservoirs are formed by the construction of dams across the river converting flowing water into a stagnant one submerging terrestrial plants and organic matters. The CO_2, CH_4, and N_2O released are attributable to the microbial decomposition of terrestrial organic matter. Most of the world's river becomes supersaturated with greenhouse gases (GHGs, *i.e.*, CO_2, CH_4, and N_2O) due to the input of carbon (C) and nitrogen (N) from land to water and thus served as significant sources of GHGs to the atmosphere [18] [19] [20].

It is, therefore, necessary to accurately estimate the atmospheric dynamics of greenhouse gas (GHG) fluxes to gain an insight into the global carbon (C) budget. Thus, projections on the course of climate change can be prepared.

2. Inland Water Bodies as Sources of Greenhouse Gases Emission

Inland water bodies such as rivers, estuaries, reservoirs, lakes, wetlands, etc. act as a sink for large quantities of carbon in their sediments and also release CH_4 and CO_2 into the surrounding atmosphere [20] [21]. DelSontro *et al.* [22] estimated that GHG emissions from lakes and impoundments are equivalent to ~20% of global fossil-fuel CO_2 emission (*i.e.*, 9.3 PgC-CO_2yr^{-1}) and projected that emission will intensify even further with the continued eutrophication of Earth's lentic ecosystems. The sewage discharge into the aquatic ecosystems like rivers, lakes, oceans, estuary, etc. leads to an increase in carbon and nitrogen. This results in an increase in GHGs emissions from these aquatic ecosystems due to nitrification, denitrification, microorganism respiration, and methanogenesis of the dissolved carbon and nitrogen nutrients. Thus, aquatic ecosystems play a crucial role in global carbon and nitrogen biogeochemical cycles and are considered as concerning sources of GHGs emissions [23] [24]. Hence, studies on GHGs emissions from aquatic ecosystems had drawn significant attention in recent years.

Emission from dry and dysfunctional inland waters are the blind spots in the global carbon cycle and the addition of emission from these water to CO_2 emissions from inland waters at the global level could result in the rise of 0.22 PgCyear^{-1} or ~10% of total fluxes [25].

India has a diverse range of aquatic resources that comprise an extensive network of 29,000 km rivers; 128,000 km man-made canals, 3.15 million ha of reservoirs; 0.3 million ha of estuaries; 2.36 million ha of pond and tanks; 0.19 million ha backwater, and lagoons; 1.2 million ha of floodplain wetlands and lakes [26]. The role of different types of inland water ecosystems towards GHGs emissions is discussed below.

2.1. Reservoirs

Reservoirs are man-made impoundments created by obstructing surface flow, by erecting a dam of any description across a river, stream, or any course of water with the main objective of irrigation, hydro-electric generation, water supply, and flow balancing. India is blessed with 3.15 million ha of reservoirs having tremendous potential for inland fisheries development in India. Dams are constructed across rivers for many purposes and act as the single largest anthropogenic source of CH_4 which is around 23% (according to the National Institute of Space Research (INPE), Brazil) of the methane emissions due to human activities. According to INPE, maximum gas emission (around 95% of CH_4) in the reservoir's surface occurs at turbines and spillways which are several kilometers downstream. It was also reported that hydro-power plants in the tropics with large reservoirs can be more impactful on global warming than power plants run by fossil fuel which generates equivalent amounts of electricity [6]. The GHG emission from reservoirs is highest in tropical and sub-tropical climates. India being a sub-tropical country, the emission of GHG in Indian reservoirs may be high but it is still unknown as hardly any such study has been conducted in the country so far.

The dam construction and formation of reservoirs lead to rotting of submerged vegetation and increase of organic matter which act as a source of CH_4 and CO_2 emission. Some other related activities which contributed to GHGs emissions are the fossil fuels and construction materials used during the erection of dam, clearing of land for establishing resettlement sites, essential lines of transmission and roads, and the expansion in irrigated farming (a significant reason for methane emissions).

2.2. Wetlands and Lakes

Wetlands are ecotone between terrestrial and aquatic conditions and the waterlogged soil is the main characteristic of wetlands. Wetlands, as defined by Ramsar convention, include areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters. India has 1.2 million hectares of floodplain lakes and wetlands where the rural population depends for their livelihood as the activity of traditional fisheries [27]. Wetlands are generally considered as a sink for large amounts of carbon, containing about one-third of the global soil carbon stock

[28]. The flooded soils in wetlands retain soil carbon as they have low oxygen levels leading to decrease rates of decomposition [29]. Greenhouse gas emission differs according to the types of wetlands and soil conditions. Wetlands are usually known for mass carbon storage and sequestration in form of biomass [29] [30]; however, they are also a prominent source of GHGs (e.g., CH_4, N_2O, etc.). Nutrients and lake size drive aquatic CO_2, CH_4, and N_2O emissions, and CO_2 emission rates declined with size across different levels of productivity [22]. This dual nature of wetlands is a very peculiar property and not so well understood, even though it is noticeably clear that under certain circumstances same wetlands could either be net sink or net source of GHGs [31]. Natural wetlands are very wet regions where the soils emit methane. Further, the soils in wetlands mostly remain in anaerobic conditions under a reduced state which favors the decomposition of organic matter into CH_4. Thus, under these circumstances, wetlands are aptly considered GHG sinks. Methane emissions are controlled by many variables like water depth, climatic condition, soil biogeochemistry, vegetation, dissolved organic carbon, total phosphorus concentration, and volume of anoxic fraction in lakes [32]. Eutrophication in global lentic aquatic ecosystems could significantly raise CH_4 emissions.

2.3. Rivers

River is any natural stream of water that flows through a channel, usually freshwater flowing towards an ocean, sea, lake, or another river. Indian River system, having a combined length of 29,000 km, which consist of 14 major rivers (catchments > 20,000 km^2), 44 medium rivers (catchments 2000 to 20,000 km^2) and innumerable small rivers and streams (catchments area < 2000 km^2). These resources may act as a significant source of GHGs to the atmosphere as they get inputs of carbon (C) and nitrogen (N) via catchment areas over land resulting in greenhouse gases (GHGs, *i.e.*, CO_2, CH_4, and N_2O) supersaturation. This happens in most of the rivers across the world. Some parts of organic carbon undergo degradation in the aquatic system and contribute to GHGs emissions [18] [33] [34]. Rivers served as an active area for GHGs emissions to the atmosphere as it is a favorable place for aqueous C and N degradation and a higher rate of intrinsic metabolic processes. On other hand, aquatic denitrification and nitrification in rivers would potentially alter the nitrogen pools hence emitting more N_2O gas in rivers [35].

2.4. Estuaries

Estuaries are partially enclosed, coastal water bodies where freshwater from rivers mixes with saline water from the ocean and are places of transition from land to sea. India is blessed with 0.29 million ha of estuaries. CO_2 and CH_4 emissions in estuaries exhibit a large spatio-temporal variability. There exists an intricate interaction of river carbon inputs, *in situ* water and sediment induced microbial processes, sedimentation and resuspension processes, tide induced exchanges

with marshes and flats, and gaseous diffusion with the atmosphere. High atmospheric CO_2 emissions at the rate of 10 - 1000 $mmolm^{-2}d^{-1}$ *i.e.*, 440 - 440,000 $mgm^{-2}d^{-1}$ occur at inshore estuarine waters, tidal flats, and sediments from marshes attributable to the net mineralization of organic carbon derived from land and marsh. Methane emissions to the atmosphere are mostly moderate in estuaries *i.e.*, 0.02 - 0.5 $mmolm^{-2}d^{-1}$ *i.e.,* 0.32 - 8 $mgm^{-2}d^{-1}$ while it may be high in densely vegetated tidal flats and marshes, specifically at freshwater sites containing sediments having CH_4-saturation [4]. The areas with a lack of sufficient oxygen and supersaturations of CO_2 are well-known features in estuaries. Due to the net sink of organic matter in the sediment, tidal marshes served as a net sink of atmospheric CO_2 [36] [37]. High-intensity sedimentary recycling of organic matter, sediments, and deposited soils from tidal flats and marshes occur at wetlands which leads to the emission of a large amount of CO_2 to the atmosphere during low tide events and spread across water column of variable height during submergence. Methane production, as well as emissions from tidal flats and marshes, are particularly high as organic matter inputs are higher at oxygen deficit depths by rooted vegetation in the sediments [38]. As compared to freshwaters, CH_4 emission would be less from the estuaries as salinity in the estuarine water is reported to inhibit the methanogenesis process [39] [40].

3. Recent Emission Rates from Different Inland Waters

Hu *et al.* [41] reported the higher rate of GHGs emission (1.20 - 2.41 times and 1.13 - 3.12 times more CO_2 and N_2O emission fluxes at the interface and the CH_4 emission fluxes was around 3.09 to 10.87 times more) in sewage draining rivers than that of the natural unpolluted river in Tianjin, China. Further, environmental features like the speed of the wind, temperature of water and air were found to influence GHGs concentrations [42].

It was estimated that inland waters induced CO_2 emission is over 2 $PgCyear^{-1}$, of which 1.8 $PgCyear^{-1}$ were emitted from rivers and streams; and 0.32 to 0.50 $PgCyear^{-1}$ were emitted from reservoirs and lakes [20] [22].

Globally, CH_4 emission was estimated to be 69 $TgCH_4\text{-}Cyr^{-1}$ of or about 0.85 Pg of C as CO_2 emission equivalents (using a 34-times conversion factor for a 100-yr time scale) from lake and impoundment [43]. Richards and Craft [44] measured GHG fluxes from a natural and a restored wetland and the recorded fluxes were 10.1 kg $CO_2\text{-}Cha^{-1}day^{-1}$, 0.2 g $CH_4\text{-}Cha^{-1}day^{-1}$, and 0.6 g $N_2O\text{-}Nha^{-1}day^{-1}$ from natural wetlands and 3.8 kg $CO_2\text{-}Cha^{-1}day^{-1}$, 0.1 g $CH_4\text{-}Cha^{-1}day^{-1}$, and 0.4 g $N_2O\text{-}Nha^{-1}day^{-1}$ from restored wetlands.

Deemer *et al.* [5] estimated the global GHG flux on a CO_2-equivalent basis (100-year horizon) from reservoirs using the dataset of 267 reservoirs from the six continents (North America, South America, Europe, Africa, Asia, and Australia), and the estimated flux to be 606.5 $TgCH_4\text{-}Cyear^{-1}$, 134.9 $TgCO_2\text{-}Cyear^{-1}$, and 31.7 $TgN_2O\text{-}Nyear^{-1}$.

GHG Emission from Inland Water Surface—Few Studies Conducted in India

Studies on the estimation of GHG emission from Indian water bodies are very few and little attention has been paid in this subject area. Thus, it is still a virgin area in the country while such studies are quite common in countries like Brazil, the USA, China, etc. since the 1990s. India being a sub-tropical country, the emission of GHG in Indian reservoirs may be high but it is still unknown as hardly any such study has been conducted in the country so far. Only a few reports are available which are summarized in Table 2.

Table 2. GHG emission from different inland water bodies—Few studies conducted in India.

Authors	Area of study	Findings
Ghosh *et al.* [45]	Saptamukhi creek, Sundarban	Recorded CO_2 emission as 56.7 ± 37.4 $mmolm^{-2}day^{-1}$
Biswas *et al.* [46]	Estuaries (Muriganga, Saptamukhi, and Thakuran) of the Sundarban mangrove ecosystem	Dissolved CH_4 concentrations in the Sundarban estuarine systems ranged between 11.0 and 129.0 $nmolL^{-1}$ with emission rates between 1.97 and 134.6 μmol m^2day^{-1}
Rajkumar *et al.* [47]	Adyar River and Estuary	Emissions fluxes for the whole Adyar system ~2.5 × 10^8 g CH_4yr^{-1} and ~2.4 × 10^6 g N_2Oyr^{-1}
Datta *et al.* [48]	Integrated rain-fed rice-fish farming system	Fish rearing increased CH_4 emission from field plots planted to 2 varieties of rice cultivars with 112% increase in CH_4 emission and 74% respectively in both the varieties. On the contrary, fish stocking reduced N_2O emission from field plots planted to both the rice varieties.
Selvam *et al.* [49]	45 water bodies include seven lakes, 10 ponds, 11 rivers, six open wells, five reservoirs, three springs, and three canals in Tamil Nadu, Kerala, and Andhra Pradesh	The total CH_4 flux (including ebullition and diffusion) from the 45 systems ranged from 0.01 to 52.1 $mmolm^{-2}d^{-1}$. The mean surface water CH_4 concentration was 3.8 to 14.5 μM CO_2 fluxes ranged from 28.2 to 262.4 $mmolm^{-2}d^{-1}$
Linto *et al.* [50]	Mangrove-associated waters of the Andaman Islands (Wright Myo; Kalighat)	Estimated mean tidal creek emissions were ~23 - 173 $mmolm^{-2}day^{-1}$ CO_2 and ~0.11 - 0.47 $mmolm^{-2}day^{-1}$ CH_4 Total emissions from contiguous inshore waters are ~1.9 × 10^{11} $molCO_2yr^{-1}$ and ~3.0 × 10^8 $molCH_4yr^{-1}$ from mangrove-influenced water
Attermeyer *et al.* [51]	Small water-harvesting lake in South India	Analyzed the effect of floating macrophytes on CO_2 and CH_4 emissions. The CO_2 and CH_4 emissions from areas covered by water hyacinths were found reduced by 57% compared with that of open water.
Shaher *et al.* [52]	Sewage-fed aquaculture ponds, East Kolkata Wetlands	Observed mean summer air-water CH_4 fluxes in the sewage fed aquaculture ponds having a depth of 1.1 m and 0.6 m were 24.79 ± 12.02 $mgm^{-2}h^{-1}$ and 6.05 ± 3.14 $mgm^{-2}h^{-1}$ respectively and CH_4 fluxes in the ponds were found positively correlated with water temperature
Kawade *et al.* [7]	Tehri hydropower reservoir, India	Tehri reservoir is a source of CO_2 with gross CO_2 emission of about 0.30 ± 0.15 Gg $CO_2km^{-2}yr^{-1}$ and net CO_2 emission of 26.89 Gg CO_2yr^{-1}

4. Mitigation Measures for GHGs Emission in Inland Water Bodies

There are opportunities to mitigate climate change through carbon sequestration and other management interventions minimizing carbon dioxide, nitrous oxide, and methane emission from inland open waters as wetlands and coastal mangroves are well known worldwide for their significant role in the storage of carbon. Globally, the coastal mangrove forests have been known to store relatively far more carbon vis-a-vis other forest-type systems [53]. The presence and prominence of deep organic-rich soils enable the mangrove forests to sequester huge amounts of carbon. Further, on an average per-unit-area basis these mangrove carbon stores are around five times in comparison to tropical terrestrial, temperate and boreal forests [54]. The settlement of organic and inorganic matter at sediment surface is allowed due to the presence of intricate root systems of mangroves which slows down and dissipates the incoming tidal currents. Further, inherent lower oxygenation also reduces the rate of decay thus driving a higher rate of carbon accumulation in the soil. This feature allows mangroves to store more carbon reserves than most tropical terrestrial forests along with their soil. These intriguing features further reaffirm the potential importance of mangroves and their role in the management of climate change issues.

5. Methods of Estimation for Greenhouse Gas Emission from Different Inland Water Bodies

Global climate change is driven by the efflux of GHGs like CO_2, CH_4, and N_2O. Assessment of the amount of GHGs released is crucial for predicting the status of climate change. Quantification of the concentration and fluxes of GHGs across human-impacted catchments from source to sea is of concern in the present day. The two-layer model of diffusive gas exchange and static headspace gas chromatography method are two common methods used for the quantification of GHGs emissions.

5.1. Closed-Chamber Method/Two-Layer Model of Diffusive Gas Exchange

A floating closed compartment is allowed to float at the surface of water and gas accumulation inside the compartment is measured in this method. Open-ended floating chambers are utilized in trapping the GHGs emitting over the water surface [15] [32] [55]. Floating chambers can be coated with paint or aluminum tape to avoid the entry of sunlight and reduce the heating of the sample. The chambers can be made of a chemically inert material like PVC/plastic buckets of around 6.5 L volume with a floating collar to maintain the desired level of water submergence (around 3 cm). Polyethylene is fixed over the chambers of the floating device. Nearly 2 cm of the chamber wall is allowed to submerge ensuring an airtight seal in between the chamber and surface water while reducing natural water turbulence impact below the chamber. The chamber is fitted with

transparent PVC tubing having 3-way Luer-lock valves to transfer gas samples into 60 ml plastic syringes. An initial ambient air sample (around 2) is to be collected at the time of setting the chamber. The free-floating of the chamber is allowed over the water and final samples are necessary to collect from the individual chamber at one-hour intervals. At the time of sampling, the gas accumulated in the chamber should be mixed by pumping about 3 times with an attached syringe to the chamber. After this, gas samples should be transferred to a 20 ml glass vial containing saturated sodium chloride (NaCl) solution lacking headspace without any delay. The glass vial must be capped with a stopper and an aluminum seal. The glass vial should be held upside down at the time of sample transferring, allowing the excess NaCl to pass through a separate needle. Thus, undiluted gas sample collection can be done for storage until analysis. A Tedlar bag is an alternate option for the glass vial discussed above. Silicon tubing is used for connecting the air sampling pump with the inlet and outlet chamber and Tedlar bag incorporating a three-way stopcock. To ensure effective mixing of gas samples, the sucked air is discharged from the inlet to the outlet chamber using an air sampling pump. After this, the three-way stopcock is used to transfer the collected GHGs sample into a Tedlar bag. Constant headspace in the ice-box is maintained for transporting GHGs fluxes collected at 60 minutes intervals in different Tedlar bags to the laboratory within 72 hours.

GHGs are analyzed gas chromatograph in two different steps viz., calibration of GC using analytical standard gas and then the estimation of GHGs in samples. Methane is detected in FID (Flame Ionization Detector) and CO_2 in TCD (Thermal Conductivity Detector). Carbon dioxide can also be detected in FID by using a methanizer. ECD (Electron Capture Detector) is used for the detection of N_2O. The quantification of GHGs is carried out based on the response of standard GHGs in the chromatogram.

5.2. Collection and Estimation of Dissolved GHGs

5.2.1. Static Headspace Gas Chromatography Method or Headspace Equilibration Method [15]

This method is used to analyze the dissolved GHGs in water samples. This can be done in different ways according to the literature available. Glass bottles of the desired size can be used for the collection of the water sample. Water samples thus collected (40 ml) should be equilibrated with ambient air (20 ml) by shaking underwater [56]. Sub-sampled or whole of equilibrated headspace is stored in airtight Exetainer vials. Sampling is to be done in duplicate or triplicate for quality control. GHGs concentration could be measured using a gas chromatograph with a flame ionization detector and electron capture detector. For DIC measurement, the samples are to be stored in gas-tight brown glass bottles (around 500 ml) with 100 µl $HgCl_2$ to prevent biological degradation and light. For DOC, the sample is to be stored in 500 ml acid-washed polypropylene bottles. The bottles are to be stored at −18˚C for laboratory measurement. HPLC is used for the detection of Dissolved inorganic nitrogen (DIN: NO_3^-, NH_4^+ and

NO_2^-) in water. TOC analyzer is used for detection of DIC (comprising HCO_3^-, CO_3^{2-} and CO_2), DOC.

100 ml sub-surface water sample (0.2 m in the water column) in triplicate is collected from fixed axial transects using Ruttner water sampler for dissolved CH_4, N_2O, and Dissolved Inorganic Nitrogen (DIN) (NO_3^-, NO_2^- and NH_4^+) analyses. Samples are then inoculated with 100 µl $HgCl_2$ to stop any microbial activity and stored in dark at 4˚C for HDPE bottles. Dry ice is used to store the filtrates while transporting to the laboratory within 12 h period and further storage at −40˚C for a maximum period of seven days before analysis. A single-phase equilibration gas chromatography, with electron capture detection (ECD) for N_2O and flame ionization detection (FID) for CH_4 [57] is then used for analyzing the concentration of dissolved N_2O and CH_4.

5.3. Recent Approaches to Understanding More about GHGs Emission

Over the last decade, the significant improvement in the use of statistically more robust designs [58] [59] coupled with improved and newer sensing technologies [42] [60] [61] [62] have paved the way for more accurate GHGs measurement from aquatic systems. This coupled with relatively increasing numbers of observations globally has enabled limnological researchers to identify the variables responsible more clearly for controlling GHGs emission rates at broad spatial scales.

5.3.1. Eddy Covariance Method

Eddy covariance method is an advanced technique that directly measures the continuous greenhouse gas emission over a larger area with detailed information on the short-term variation of flux, having high precision with a high sampling rate and short response time [63]. Gas fluxes, emission, and exchange rates are carefully characterized from a single point *in situ* measurements using permanent or mobile towers, or moving platforms such as automobiles, helicopters, airplanes, etc. Eddy covariance can characterize areas ranging from hundreds of square meters to tens of square kilometers depending on the measurement height and surface conditions. It has 3-dimensional sonic anemometers which measure the wind direction and its speed. It has sensors for N_2O, CH_4, CO_2, and water vapor (H_2O) along with sensors for measurements of incoming and outgoing, short wave and longwave radiation, and photosynthetically active radiation (PAR). The 3-dimensional wind speeds from the sonic anemometer and other variables, usually gas concentration, temperature, or momentum are decomposed into mean and fluctuating components. By finding the covariance between the vertical wind speed fluctuations with fluctuation in temperature, humidity, carbon dioxide, methane, sensible and latent heat, etc., fluxes of these variables are determined. The covariance is calculated between the fluctuating component of the vertical wind and the fluctuating component of gas concentration. This method is widely used for quantifying GHG emission rates from natural, urban and agricultural ecosystems. However, its application in inland aqua-

tic ecosystems such as lakes and reservoirs is relatively new or limited to only a few mangrove ecosystems [64], marshy wetlands [65] [66] [67], etc. It is always more advantageous than the traditional closed chamber method in the measurement of GHG, but its main disadvantage is its high cost, poor sensor performance during wet conditions, and requirement of a skilled person for its operation and data recording than the closed chamber technique.

6. Future Research Needs and Focus Areas in the Indian Scenario

Inland fisheries in India are threatened by climate changes such as a change in temperature, precipitation, droughts, storm, floods that affect mostly production, productivity and ultimately affect the fishers' livelihood. The fisheries are impacted owing to intricate interactions of different physico-chemical environmental variables such as winds, temperature, vertical mixing, salinity, pH, oxygen concentration, and others. The impact on the physiology, development rates, reproduction, behavior, and survival of individuals are associated with direct effects while changes in critical ecosystem processes, food production, abundance, and distribution of predators, competing communities, and pathogen are having indirect association with the impacts of rising GHGs emissions and its impact on climate change. In this scenario, the researchable topic of the C efflux from exposed sediments in dry streams, reservoirs, lakes, rivers, and ponds, into the atmosphere can be considered the need of the hour in biogeochemistry research and for mitigating climate change crisis owing to increasingly higher rates GHGs emission from natural and impacted aquatic ecosystems.

It is limited, or no studies have been done so far in our country with regards to the levels of greenhouse emission from inland open water bodies and their impact on the inland fisheries. Therefore, one of the most important steps which need to be taken at this point would be the assessment and monitoring of greenhouse gas emissions in inland open water bodies as well as necessary regulations should be made to mitigate this problem. Only after estimating GHG emission in a quantified manner, the carbon storage and sequestration ability of the wetlands and mangroves can be properly understood.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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