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Technical Report

Assessment of Greenhouse Gas Emissions from Wastewater-Based Aquaculture Systems

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November 2026



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Acknowledgements
This work was conducted under the CGIAR Sustainable Animal and Aquatic Foods Program. We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund: https://www.cgiar.org/funders/

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Suggested citation
Chanu, Thangjam Nirupada, Elizabeth Haobam, Gunjan Karnatak, et al. 2026. *Assessment of Greenhouse Gas Emissions from Wastewater-Based Aquaculture Systems.* International Water Management Institute (IWMI).

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Summary

The project entitled “Study on Greenhouse Gas (GHG) Emissions linked to wastewater-based aquaculture” was undertaken in the East Kolkata Wetlands (EKW), a globally significant Ramsar site recognized for its unique wastewater-fed aquaculture system. The study aimed to quantify emissions of the primary greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and to study the environmental drivers of GHG emissions in the East Kolkata Wetlands in India.

Field sampling was carried out from August to October 2025, covering two distinct seasons, viz. the monsoon and post-monsoon. The results represent a limited number of sampling events (one day per *bheri* per month) at five selected *bheris* and should be regarded as preliminary. It revealed marked spatial variability in GHG emissions, with sewage channels acting as major hotspots of CH_4 and CO_2 release due to high organic matter loading, reduced oxygen conditions, and intense microbial decomposition. In contrast, aquaculture *bheris* exhibited comparatively moderated emissions, reflecting the progressive transformation and ecological assimilation of wastewater within the wetland system. Nitrous oxide (N_2O) emissions remained consistently low across sites, indicating limited spatial variation in nitrogen-related gaseous losses.

Water quality assessments demonstrated eutrophic to hypereutrophic conditions characterized by elevated nutrient concentrations and high primary productivity, confirming the multifunctional role of EKW *bheris* in wastewater treatment, nutrient recycling, and fish production. Significant relationships between GHG emissions and environmental variables such as Biochemical Oxygen Demand (BOD), dissolved oxygen (DO), pH, and nutrient concentrations highlighted the importance of organic enrichment and redox processes in regulating carbon and nitrogen cycling. Sediment analyses further indicate substantial accumulation of organic carbon and nutrients, emphasizing the role of sediments as both nutrient reservoirs and active regulators of biogeochemical processes.

The study generated preliminary, site-specific baseline estimates of CH_4, CO_2, and N_2O emissions from one of the world’s largest wastewater-fed aquaculture systems and provided valuable insights into the interactions between wastewater management, aquaculture productivity, and GHG dynamics. The findings underscore the dual role of EKW as an efficient nature-based wastewater treatment system and a source of carbon-based greenhouse gases, thereby contributing important information for regional carbon budgeting and climate change assessments.

The outcomes of this study will support the development of sustainable management strategies aimed at balancing wastewater remediation, aquaculture production, ecosystem services, and climate mitigation within the East Kolkata Wetlands. However, the study also highlights the need for long-term monitoring to capture seasonal and interannual variability and to improve the accuracy of wetland-scale GHG emission estimates.

Quantitatively, the sewage-feeder channel was the main emission hotspot among the sampled sites, with mean fluxes of 1174.9 ± 1616.0 mg CH_4–C m^{-2} day^{-1} and 553.6 ± 437.7 mg CO_2–C m^{-2} day^{-1}. These were roughly three to seventy-five times (CH_4) and seven to thirteen times (CO_2) higher than those recorded within the aquaculture *bheris*, where fluxes declined progressively from the inlet (S1) to the outlet (S3). The large standard deviation in the sewage channel reflects a small number of exceptionally high values, and the mean should therefore be interpreted with caution. Nitrous oxide fluxes were uniformly low (0.011–0.249 mg N_2O–N m^{-2} day^{-1}). Biochemical and chemical oxygen demand (BOD, COD) fell by roughly 50% between the sewage channel and the *bheri* outlets, consistent with the wastewater-treatment function of the system. Carlson Trophic State Index values of 80–91 indicate hypereutrophic conditions across all sampled *bheris*. Because methane has a global-warming potential approximately 27–30 times that of CO_2 over a 100-year horizon (IPCC, 2021), CH_4 was the dominant contributor to CO_2-equivalent emissions at the sampled sites. These findings are preliminary and limited to five selected *bheris* and the August–October 2025 sampling period. They should not be generalised to the wider East Kolkata Wetlands or used directly for national greenhouse-gas inventories; longer-term, spatially representative monitoring would be needed before such use.*bherisbheribheris*

1. Background and Objectives

Wastewater-fed aquaculture systems have long supported food production in many tropical and subtropical regions, particularly in peri-urban landscapes where nutrient-rich effluents are readily available. These systems are often regarded as efficient, low-cost models of circular resource use because these wetlands convert organic waste into fish biomass while reducing the burden on conventional wastewater treatment. Yet, as global attention intensifies around the climate impacts of managed freshwater environments, important questions remain about the magnitude of primary greenhouse gas (GHG) (e.g., carbon dioxide, methane, and nitrous-oxide) emissions from wastewater-based aquaculture and how these emissions are comparable with other land-use systems, such as agricultural fields or conventional aquaculture ponds.

Freshwater wetland environments are recognized contributors to global methane budgets, driven largely by organic loading and persistent anaerobic conditions within stagnant water columns (Saunois et al., 2020; Yang et al., 2011). Wastewater inputs can amplify these drivers, creating conditions that can favour strong methane and carbon dioxide production. Studies from treatment receiving wetlands and constructed aquatic systems, such as dams, show that nutrient-rich effluents stimulate microbial processes responsible for GHG generation (Yin et al., 2023; Jahangir et al., 2016). However, the degree to which these mechanisms operate in wastewater-fed aquaculture ponds where water exchange, fish grazing, sediment disturbance, and photosynthetic activity interact remains insufficiently quantified.

At the same time, aquaculture itself has emerged as an expanding source of greenhouse gases. Recent global assessments highlight substantial variation in CH_4, CO_2 and N_2O emissions across production systems, influenced by organic inputs, hydrology, and pond management (MacLeod et al., 2020; Kosten et al., 2020). Wastewater-fed ponds share some of these characteristics but differ in their reliance on external organic-rich inflows rather than formulated feeds or fertilizers. This distinction may alter both emission patterns and productivity outcomes. Without direct measurement, it is difficult to establish whether wastewater-based aquaculture poses a larger or smaller climate footprint than other forms of aquaculture.

Agricultural systems provide another important point of comparison. Methane and nitrous oxide emissions from rice fields, fertilized croplands, and flooded soils are widely reported contributors to global GHG budgets, shaped by water management, nutrient loading, and microbial pathways (Saunois et al., 2020). Yet few studies have examined how emissions from agricultural landscapes are comparable with those from wastewater-fed aquaculture systems operating within the same regional context. Such comparisons are needed to understand whether shifting land use toward wastewater reuse in aquaculture represents a climate-efficient alternative or whether it redistributes emissions among sectors.

Inland aquatic ecosystems are now recognized as major yet highly uncertain components of the global greenhouse gas budget. Freshwater systems alone are estimated to emit at least 103 Tg of methane annually sufficient to offset a substantial fraction of the terrestrial carbon sink (Bastviken et al., 2011) and the most recent global assessments attribute a large and growing share of atmospheric methane to aquatic and human-influenced sources (Saunois et al., 2020). Small, nutrient-rich and hydrologically dynamic water bodies such as ponds and shallow wetlands tend to exhibit the highest area-specific fluxes and the greatest variability, yet they remain sparsely represented in both bottom-up inventories and process-based models (Rosentreter et al., 2021). Wastewater-fed aquaculture ponds combine several of the attributes associated with elevated emissions continuous organic and nutrient loading, shallow depth, warm temperatures and frequent oxygen depletion making them plausible but poorly constrained hotspots of carbon and nitrogen gas exchange.

Aquaculture is among the fastest-growing food-production sectors globally, and its climate footprint is expanding accordingly. The adoption of intensive, industrial-scale systems has been shown to increase pond-level global-warming potential several-fold, driven predominantly by rising methane emissions, with sectoral emissions projected to increase markedly by mid-century (Yuan et al., 2019). Global syntheses nonetheless reveal wide variation in reported CH_4 , CO_2 and N_2 O fluxes across production systems, reflecting differences in feed and fertilizer inputs, hydrology and pond management (MacLeod et al., 2020; Kosten et al., 2020). Wastewater-fed systems occupy a distinctive position within this spectrum: rather than relying on formulated feeds, they are sustained by external, organic-rich effluents, a difference that may reshape both the magnitude and the relative composition of their emissions.

Nitrogen-cycling gases warrant particular attention. Aquaculture has been identified as a potentially important and rapidly growing anthropogenic source of nitrous oxide, a gas whose global-warming potential greatly exceeds that of CO_2 , and which is now a leading contributor to stratospheric ozone depletion (Williams and Crutzen, 2010; Hu et al., 2012). In nutrient-rich aquatic systems, N_2 O is generated as an intermediate or by-product of microbial nitrification and incomplete denitrification, and its emission is strongly modulated by dissolved-oxygen availability, nitrogen speciation and redox conditions (Hu et al., 2012). Whether wastewater-fed aquaculture amplifies or suppresses N_2 O relative to conventional systems depends on the balance between these competing pathways and therefore cannot be inferred without direct measurement.

The East Kolkata Wetlands (EKW) provide an exceptional setting in which to examine these questions. As one of the world's largest and longest-operating wastewater-fed aquaculture landscapes, and a Ramsar site of international importance, the EKW simultaneously delivers wastewater treatment, food production and livelihood support for a major metropolitan region. Despite this global significance, quantitative estimates of greenhouse-gas exchange from the EKW and from comparable hybrid wastewater–aquaculture systems more broadly remain scarce, and emission factors for such systems are poorly represented in international inventory guidance (IPCC, 2019). Generating robust, site-specific flux estimates may, in the longer term, be relevant toe both to India's climate-reporting obligations and to the wider effort to reconcile food production with climate mitigation in peri-urban wetland systems.

These knowledge gaps motivated the need for a comprehensive assessment of GHG fluxes across wastewater-based aquaculture systems adjacent to agricultural landscapes. By quantifying CH_4, CO_2, and N_2O emissions across these settings, the proposed study aims to generate evidence to help determine the environmental trade-offs embedded in wastewater reuse for food production. Understanding whether high productivity comes at the cost of increased emissions or whether management interventions can balance both goals is essential for developing sustainable aquaculture strategies aligned with climate commitments. The present study was structured around three guiding questions: (i) how do CH_4 , CO_2 and N_2 O fluxes vary spatially across the sewage channel, the inlet–middle–outlet gradient of the *bheris*, and an upland reference site; (ii) which water- and sediment-quality variables most strongly regulate these fluxes; and (iii) what do the resulting emission patterns imply for the management and climate accounting of wastewater-fed aquaculture systems? Based on the above background, the objectives of the present study are formulated as follows:

- To quantify major GHG emissions (CO_2, CH_4, N_2O) associated with aquaculture systems within selected sub-catchments of the wetland.
- To study environmental drivers of GHG emissions in the East Kolkata Wetlands.

The conceptual framework examines the wastewater–aquaculture linkage as a coupled biogeochemical system to understand the drivers, processes, and spatial dynamics of greenhouse gas (GHG) emissions from wastewater-fed aquaculture systems (*bheris*) in the East Kolkata Wetlands (Figure 1). It hypothesizes that wastewater inflows, organic matter and nutrient loading, seasonal variations, and aquaculture management practices influence carbon and nitrogen cycling through microbial processes, including aerobic respiration, methanogenesis, nitrification, and denitrification. These processes regulate the production, consumption, and release of CO_2, CH_4, and N_2O across the water–sediment–atmosphere interface, resulting in spatial and temporal variations in GHG fluxes. The study seeks to quantify these emissions, identify key biogeochemical drivers and emission hotspots, and assess the implications for the net carbon balance of wastewater-fed aquaculture. The findings will inform management strategies that minimize GHG emissions while sustaining wastewater treatment, nutrient recycling, and aquaculture productivity, thereby supporting climate-responsive management and policy interventions for the East Kolkata Wetlands.

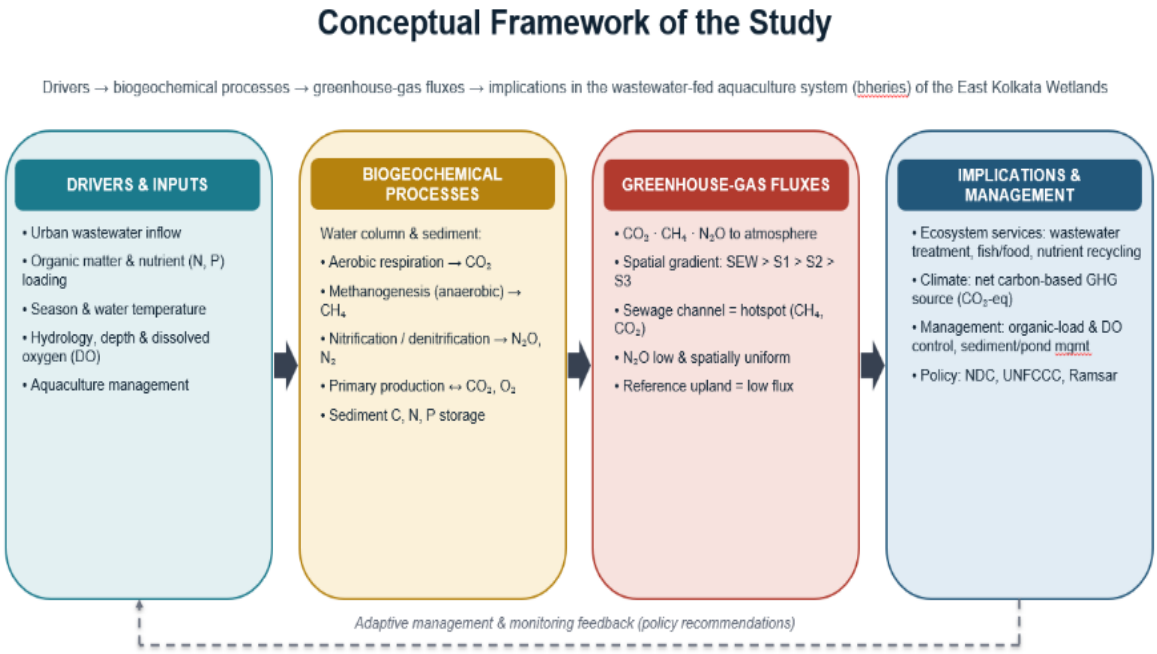


Figure 1: Conceptual framework of the study integrating greenhouse emissions related to wastewater aquaculture

2. Study area and methodology

2.1 Study area

The experiment was carried out in the northern part of East Kolkata Wetlands (EKW) (Fig. 2), a Ramsar-designated sewage-fed wetland system, locally called *Bheri* located on the eastern periphery of the Kolkata metropolitan area, West Bengal, India. A ***bheri*** (Bengali word meaning "water body for fish cultivation") is a traditional shallow wastewater-fed fish pond that utilizes nutrient-rich urban wastewater for aquaculture and natural wastewater treatment. Approximately 264 *bheris* operate within the EKW, producing about 20,000 MT of fish and 50,000 MT of vegetables annually while irrigating nearly 4,700 ha of paddy fields. Recognized as a Ramsar Site since 2002, EKW is globally acknowledged as an outstanding example of sustainable wetland management, wastewater reuse, and circular resource recovery (Ghosh, 1999; Bunting et al., 2010; EKWMA and WISA, 2021).

Five sewage-fed *bheris* (Fig. 2) selected for the study were: Sukanta Nagar *Bheri* (22.55894°N, 88.42015°E), 4 No. *Bheri* (22.55792°N, 88.42606°E), Nuner *Bheri* (22.55053°N, 88.41333°E), Natar *Bheri* (22.54998°N, 88.42508°E), and Sahebmara *Bheri* (22.54920°N, 88.43299°E). The total area of the studied *bheris* ranged between 25.29 and 197.05 ha, with Sukanta Nagar being the smallest (25.29 ha) and Sahebmara the largest (197.05 ha). The areas of 4 No. *Bheri*, Natar *Bheri*, and Nuner *Bheri* were 45 ha, 166.93 ha, and 53.12 ha, respectively. Each *bheri* functions as a flow-through aquaculture system receiving domestic wastewater from the Kolkata city through an interconnected canal network that supplies nutrient-rich effluent, supporting natural wastewater treatment and fish

production. At each *bheri* (Figs. 2 to 5), five sampling sites were selected: the first point near the inlet (S1), second at the midpoint (S2), third at the outlet (S3) of the *bheri*, fourth at the sewage feeding channel (SEW) and fifth was an upland reference point (REF) to capture spatial variability in GHGs flux dynamics, drivers of GHG emissions in EKW, viz., water and sediment quality parameters related to sewage inflow, internal circulation, and effluent discharge (Fig. 3 and Fig. 5). Owing to the limited project period (July to November 2025), sampling was conducted in August, September and October 2025, when hydrological fluctuations, nutrient loading and microbial activity are strongly influenced by wastewater flows and the seasonal rainfall pattern. Accordingly, the findings are limited to the selected sites and this sampling window.

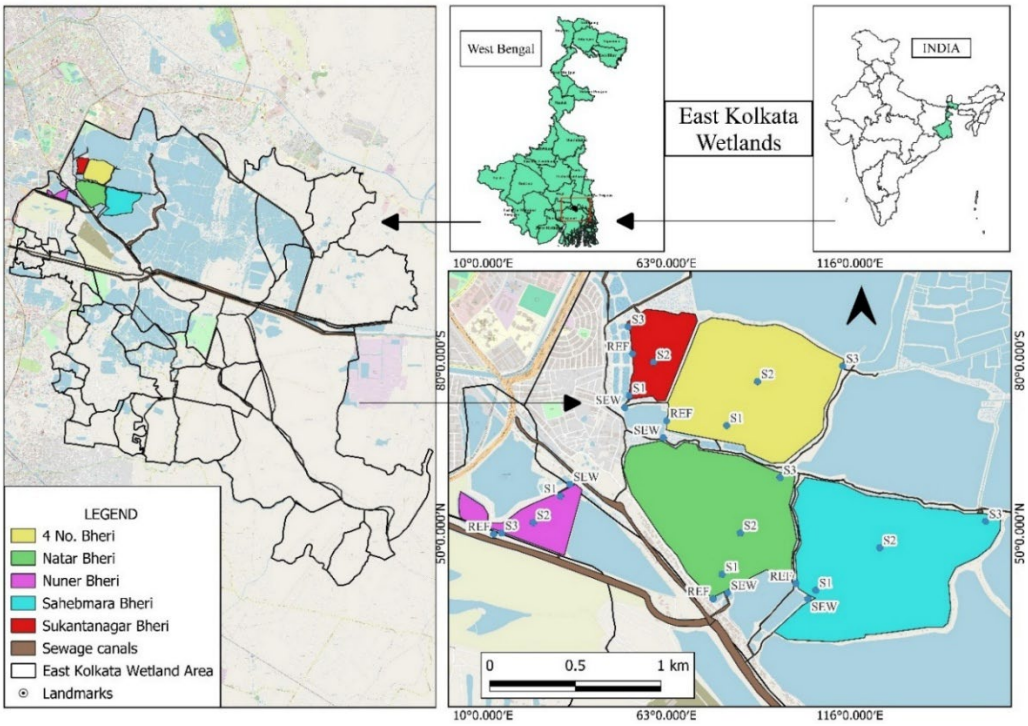


Figure 2**:** Study area map (indicating different study sites as SEW – sewage channel, S1 – near the inlet of *bheri*, S2 – mid-point of the *bheri*, S3 – outlet of the *bheri* and REF – reference upland site. Source: Authors

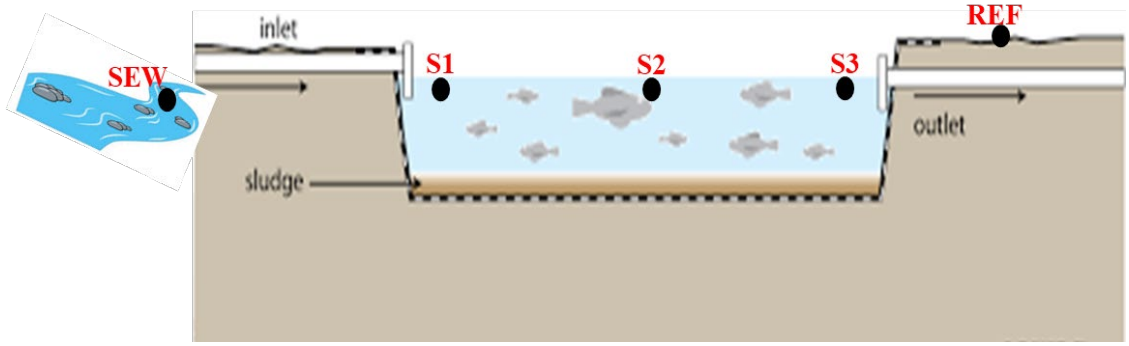


Figure 3. Diagrammatic presentation of a sewage-fed *bheri* and different sampling sites as SEW – sewage channel, S1 – near the inlet of *bheri*, S2 – mid-point of the *bheri*, S3 – outlet of the *bheri* and REF – reference upland site. Source: Authors

2.2 Methodology

2.2.1 Sample collection and analysis

Water and air temperatures were recorded during every sampling event. Gas samples were collected using cylindrical floating chambers made of acrylic sheets (Fig. 4A-C), each with a volume of about 0.03 m³ (15 cm radius and 42 cm height). For the upland reference site, smaller PVC chambers (Fig. 4D) with a volume of 0.0051 m³ (7.5 cm radius and 29 cm height) were used. These PVC chambers were inserted into the soil to a depth of roughly 10 cm to create a tight seal at the air–soil interface, following established chamber methods (Nahlik & Mitsch 2010; Parkin & Venterea 2010).



Figure 4. Sampling of GHG using floating gas collection chamber in different study sites (A) sewage channel, (B) near inlet of the *bheri*, (C) mid-point of the *bheri*, (D) sampling of GHG at reference upland site using PVC chamber. Source: Authors



Figure 5. Sampling sites (A) Sewage canal, (B) Inlet, (C) Middle and (D) Outlet site. Source: Authors

After placing the floating chambers on the water surface and PVC chambers on the soil surface, an initial gas sample was drawn immediately using a 20 ml syringe fitted with a three-way stopcock. Additional samples were collected from the same chamber after 30 and 60 minutes. Thus, on each sampling day, three time-interval samples (0, 30, and 60 min) were collected from each chamber at all sites, including the inlet, midpoint, outlet, sewage channel, and upland reference point. All gas collections were performed in triplicates at each site to avoid random

variations. For flux calculations, only the effective headspace volume was used. The floating chambers rested on the water surface (dipped ~ 2 cm), so the full chamber volume (~0.0283 m^3) was used for the water sites, whereas for the PVC chambers inserted ~10 cm into the soil only the volume above the soil surface (~19 cm; ~0.0034 m^3) was used. Sampling was carried out on one day per *bheri* per month, yielding three sampling days per *bheri* over the three-month study period. For the present study, ethical approval from IWMI-IRB Committee was secured. The study team requested respective cooperatives, managers, lease-owners, and owners to provide informed consent for collecting samples.

2.2.2 Greenhouse gas emission (GHGs) estimation

Collected gas samples were analyzed within 72 hours of sampling for CH_4, CO_2, and N_2O in a gas chromatograph (GC) (Thermo Scientific™ TRACE™ 1610 GC Greenhouse Gas GC Analyzer) fitted with three valves and two different detectors (Fig. 6). A flame ionization detector (FID) was used for analysis of CH_4 & CO_2, and micro electron capture detector (μECD) for N_2O analysis. The detection of CO_2 & CH_4 is effectively done with flame ionization using a methanizer. The gas sample passes through the methanizer, heated at 380℃, where CO_2 is reduced to CH_4 in a catalytic Ni thermal auxiliary heater, before entry into the flame ionization detector running at 250°C. The methanizer/FID combination measures low levels of CO_2 and CH_4. The micro-ECD that detects atoms and molecules in a gas through the attachment of electrons via electron capture ionization is 10-1000 times more sensitive than an FID and is used to detect N_2O. The temperatures of the column oven, μECD, and FID were maintained at 60, 300, and 250℃, respectively.



Figure 6. (A) Gas Chromatography (GC) system used for the greenhouse gas (GHG) analysis, (B) 20 ml gas collection syringe with three-way stopcock. Source: Authors

Samples were injected into the short column, which separates the components, including air (O_2), CO_2, and CH_4. All analytes after analysis of N_2O are back-flushed, and the air is vented away from the methaniser and μECD. CO_2 is converted to CH_4 through the methaniser and measured by FID, and N_2O is introduced into the micro-ECD for measurement. GC Chromeleon 7 software (inbuilt with GC) was used to automatically integrate peak areas, produce calibration curves, and calculate sample concentrations. Corrected chamber concentrations by weight were calculated from the GC results, and the density was corrected for chamber volume and temperature based on universal gas laws following a specific formula (Parkin and Venterea 2010; Nag et al. 2017) using the effective headspace volume described in Section 2.2.1. Flux rates of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) were expressed as mg CH_4-C m^{-2} day^{-1}, mg CO_2-C m^{-2} day^{-1}, and mg N_2O-N m^{-2} day^{-1}.

2.2.3 Water sampling

Sub-surface water samples were collected from the inlet area, midpoint and outlet area of the sewage-fed *bheri*, along with sewage water from the feeding channel (Fig. 7). All samples were taken in the morning (09:00–11:00 hrs.) using pre-rinsed HDPE bottles. During sampling, basic water quality parameters, including transparency, depth, temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and dissolved oxygen (DO), were measured immediately on site. Transparency was measured using a Secchi disc and depth was recorded using a depth sounder, while temperature, pH, EC and TDS were measured with pre-calibrated portable multi-parameter equipment (Model: PCSTestr™ 35; Eutech Instruments). Dissolved oxygen was determined using Winkler's method (APHA, 2012).



Figure 7. Sampling and onboard water sample analysis conducted during the project period at Natar *Bheri* Source: Authors

For nutrient analysis, subsurface water samples were collected in pre-cleaned HDPE bottles and transported to the laboratory at 4°C. Chlorophyll-a (Chl-a) was measured using the spectrophotometric method of Jeffrey and Humphrey (1975). Nitrate was determined using the phenol-disulphonic acid method, while phosphate was measured after reacting the sample with an acidic molybdate reagent containing ascorbic acid and a small amount of potassium antimony tartrate (APHA, 2012). Total nitrogen was analysed by the Kjeldahl method, in which the sample is digested with sodium hydroxide pellets and a small quantity of Devarda's alloy (Bremner, 1960). Primary productivity viz. Gross Primary Productivity (GPP), Net Primary Productivity (NPP), and Community Respiration (CR) were estimated using Gaarder and Gran's Light and Dark bottle method (1927). The initial bottle was fixed immediately to determine the dissolved oxygen level. The light and dark bottles were incubated in situ at the sampling depth (10 cm) for 3 hrs. The results of GPP, NPP and CR were calculated following Gaarder and Gran's equation (1927).

2.2.4 Sediment sampling

About 500 g of sediment was collected from the inlet area (S1), midpoint (S2) and outlet area (S3) of the sewage-fed *bheri* using a soil grab during the sampling. The samples were stored in zippered plastic bags and transported to the laboratory in an ice-packed insulated box. Sediment from the sewage channel could not be collected due to the difficulty and safety constraints of manual sampling. In the laboratory, the sediment samples were cleaned by removing visible plant debris, air-dried and passed through a 10-mesh sieve before analysis.

Moisture content was measured using the standard gravimetric method (Gardner, 1986), which involves weighing the wet sample, removing the water or moisture through oven drying in a laboratory oven at 105°C for 24 hours until all water is evaporated and the weight remains constant, and reweighing the sample to determine the amount of water removed. Soil texture was determined by the hydrometer method (Gee & Bauder, 1986). Electrical conductivity (EC) was measured with a conductivity meter (Rhoades, 1996), and pH with a pH meter using the potentiometric method (Thomas, 1996). Organic carbon was estimated using the Walkley–Black method (Mylavarapu et al., 2014). Total nitrogen was analysed using the Kjeldahl method (Bremner, 1960), while total phosphorus was determined spectrophotometrically following the molybdenum blue method (Olsen & Dean, 1965).

2.2.5 Trophic State Index

Total phosphorus (TP) and total nitrogen (TN) are widely recognized as the primary nutrients regulating eutrophication in freshwater systems, as elevated inputs of these elements tend to stimulate algal growth and accelerate shifts toward higher trophic states (Schindler, 1977; Smith, 2003). Chl-a is frequently used as an indicator of phytoplankton biomass and serves as a practical proxy for assessing trophic conditions in lakes and reservoirs (Carvalho et al., 2013; Xu et al., 2010). Among the various approaches available for evaluating trophic status,

Carlson's trophic state index (CTSI) remains one of the most commonly applied frameworks because it integrates Secchi depth, Chl-a and phosphorus concentrations into a single diagnostic measure (Carlson, 1977). In this study, CTSI values were calculated using Secchi depth (SD), TP and Chl-a to characterize the trophic state of the system (Equations 1-4). The trophic state of study sites in EKW was assessed using the CTSI, which provides a degree of the ecosystem's biological productivity, categorizing systems with a standard scale, viz., TSI <40 as oligotrophic, TSI 40-50 as mesotrophic, TSI 50-60 as meso-eutrophic, 60-80 as eutrophic and TSI >80 as hypereutrophic (Carlson, 1977; Carlson, 2007).

$$TSI(Chl) = 10\left(6 - \frac{2.04 - 0{\cdot}68\ ln(Chl)}{ln\ 2}\right)$$ ----------(1)

$$TSI(SD) = 10\left(6 - \frac{\ln(SD)}{ln\ 2}\right)$$ ----------(2)

$$TSI(TP) = 10\left(6 - \frac{\ln(\frac{48}{TP})}{ln\ 2}\right)$$ ----------(3)

$$Mean\ TSI = \left(\frac{TSI(SD)+TSI(Chl)+TSI(TP)}{3}\right)$$ ----------(4)

where TP and Chl-a are expressed in mg m^{-3} and SD in meters.

2.2.6 Statistical analysis

Statistical analyses were performed to evaluate spatial and temporal variability in GHG fluxes and their relationships with water and sediment quality parameters. Descriptive statistics were generated in MS Excel (2019), and all water quality variables except pH were normalised using a log (x + 1) transformation. One-way analysis of variance (ANOVA) with appropriate post hoc tests was conducted in SPSS version 23, and two-tailed Spearman's rank correlation analysis was used to assess associations between GHG fluxes and physico-chemical characteristics. Differences were considered significant at $p < 0.05$.

3. Analysis and Results

Section 3.1 covers the results on GHGs, water and sediment quality parameters in the studied areas while section 3.2 covers the discussions on the findings of the present studies.

3.1 Quantification of Greenhouse Gases

Descriptive statistics of the GHGs flux estimated during the study are presented in Table 1. CH_4, CO_2 and N_2O fluxes showed distinct spatial variability across the five *bheris* examined in the East Kolkata Wetlands. One-way ANOVA revealed that CH_4 and CO_2 fluxes in the sewage channel carrying raw sewage are found to vary significantly (p<0.05) from one *bheri* to the other and reference upland sites; however, there was no significant variation (p>0.05) between the months observed during the study period. N_2O flux in the *bheris*, reference upland site and sewage channel did not vary significantly between sites or months.

Figures 8-13 depict the spatial patterns of GHG fluxes across the different *bheri* sites. CH_4 and CO_2 exhibited a consistent gradient, following the order Sewage channel > Site 1 (inlet area) > Site 2 (middle) > Site 3 (outlet area), with peak concentrations at the sewage-influenced locations and a gradual decline toward the outlets. A slight deviation from this pattern was observed in Natar *bheri*, where CH_4 levels at Site 1 (inlet) exceeded those at the sewage site, likely reflecting dilution effects of incoming sewage water during these monsoon months. Unlike CH_4 and CO_2, the concentration of N_2O in majority of the *bheris* was found to be higher in site 2 (middle) such as in Natar, 4 No., and Nuner *bheri*, whereas at Sahebmara *bheri*, site 1 exhibited the maximum N_2O levels and, at Sukanta Nagar *bheri*, elevated N_2O concentrations were observed at both the sewage channel site and Site 3 (outlet area).

3.1.1 Methane (CH_4) flux

Methane emissions showed marked variation across the sites in *bheris*, the reference upland site and the sewage channel of the East Kolkata Wetlands. CH_4 flux in the sewage channel observed was statistically distinct (p<0.05) from other sites, whereas sites 1-3 and the reference site did not differ significantly from one another. The sewage channel recorded the highest CH_4 flux, with values ranging from 2.56 to 5959.66 mg CH_4-C m^{-2} day^{-1} and a mean

of 1174.89±1616.03 mg CH_4-C m^{-2} day^{-1}, which was significantly higher than all other sites. The large standard deviation reflects a small number of exceptionally high values, probably associated with episodic ebullition from the organically enriched sewage channel; the mean should therefore be interpreted with caution. The three sites of sewage-fed aquaculture *bheris* exhibited comparatively moderate to low emissions. The CH_4 flux in EKW was found in the order S1 (inlet) > S2 (mid-point) > S3 (outlet), indicating the decreasing trend of CH_4 emission towards the outlet of the *bheris* (Fig. 7 and 8). Site 1 showed a wide range (18.43 - 1398.83 mg CH_4-C m^{-2} day^{-1}) (Table 1) with a mean value of 393.63 ± 375.20 mg CH_4-C m^{-2} day^{-1}, while site 2 and site 3 recorded substantially lower fluxes (71.66 ± 114.04 and 15.51 ± 20.87 mg CH_4-C m^{-2} day^{-1}, respectively). The reference upland site displayed very low methane emissions (mean 5.71 ± 20.77 mg CH_4-C m^{-2} day^{-1}). Carbon dioxide followed the same sewage-to-outlet gradient and is described next (Section 3.1.2).

Table 1. GHGs flux from selected *bheris* of EKW

***Bheris* of East Kolkata Wetlands**										
GHGs	**S1**		**S2**		**S3**		**SEW**		**REF**	
	Range	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**	**Mean ± SD**
CH_4 (mg CH_4-C m^{-2} day^{-1})	18.43-1398.83	393.63 ± 375.20[a]	0.52-443.39	71.66 ± 114.04[a]	0.42-85.44	15.51 ± 20.87[a]	2.56-5959.66	1174.89 ± 1616.03[b]	0.039-80.76	5.71 ± 20.77[a]
CO_2 (mg CO_2-C m^{-2} day^{-1})	14.93-239.22	77.07 ± 58.79[a]	8.54-149.84	55.28± 30.89[a]	20.56-105.06	43.99 ± 22.92[a]	44.85-1367.91	553.59 ± 437.68[b]	52.29-824.29	243.23 ± 206.78[a]
N_2O (mg N_2O-N m^{-2} day^{-1})	0.019-0.11	0.048 ± 0.03[a]	0.02-0.11	0.053 ± 0.04[a]	0.02-0.08	0.048 ± 0.03[a]	0.011-0.137	0.049 ± 0.04[a]	0.031-0.249	0.082 ± 0.06[a]

*The same letter (superscripts) shows no significant variation between the sites, and different letters indicate significant differences between sites at the 5% level of significance.

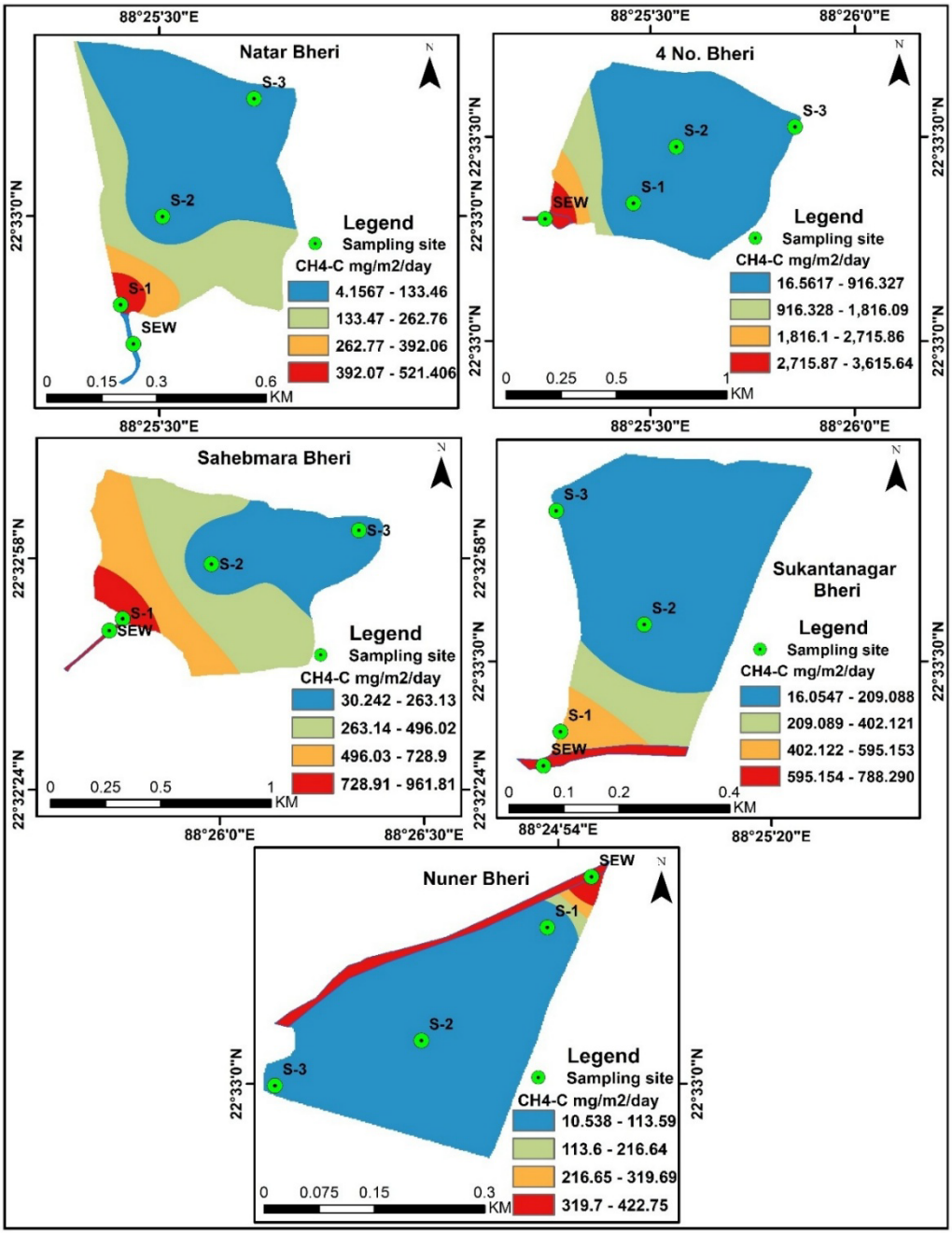
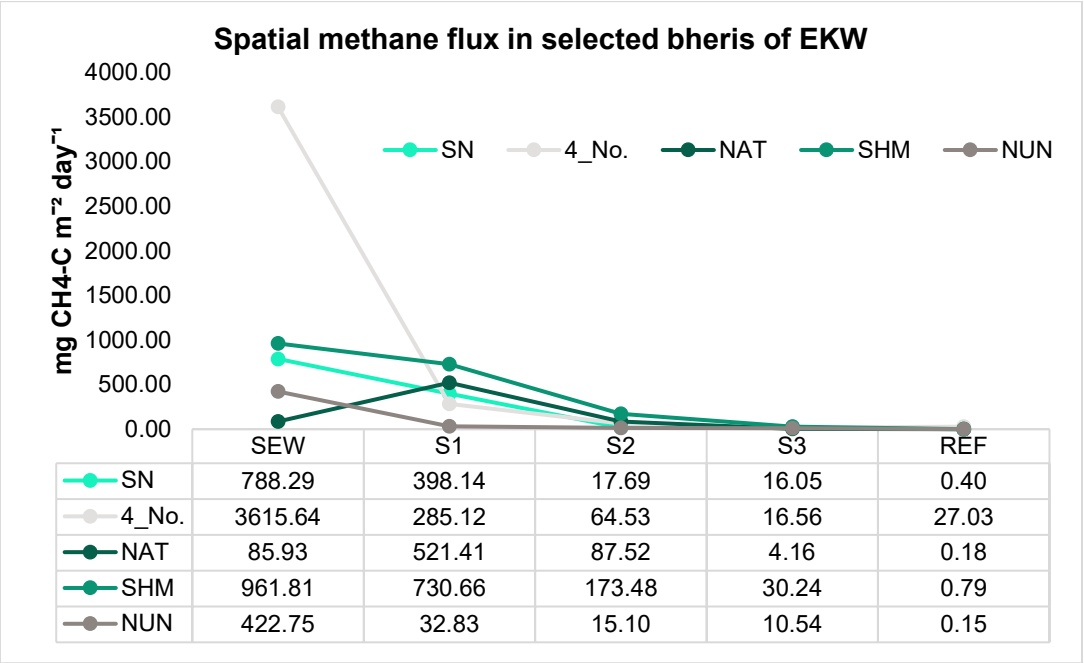


Figure 8. Spatial distribution maps of CH_4 in five *bheris* during the present study. Source: Authors



	SEW	S1	S2	S3	REF
SN	788.29	398.14	17.69	16.05	0.40
4_No.	3615.64	285.12	64.53	16.56	27.03
NAT	85.93	521.41	87.52	4.16	0.18
SHM	961.81	730.66	173.48	30.24	0.79
NUN	422.75	32.83	15.10	10.54	0.15

Figure 9. Spatial methane flux recorded in the selected *bheris* of EKW (SN: Sukanta Nagar *bheri*, 4.No.: 4 No. *bheri*, NAT: Natar *bheri*, SHM: Sahebmara *bheri*, and NUN: Nuner *bheri*). Source: Authors

3.1.2 Carbon dioxide (CO_2) flux

A similar spatial pattern of carbon dioxide emissions was observed in EKW during the present study period (Figs. 9 and 10). CO_2 flux in the sewage channel was substantially higher than at the sites of *bheris*, ranging from 44.85 to 1367.91 mg CO_2-C m^{-2} day^{-1} and averaging 553.59 ± 437.68 mg CO_2-C m^{-2} day^{-1}. In contrast, the sewage-fed *bheris* exhibited more moderate and relatively uniform CO_2 emissions. The CO2 emission in the sewage-fed aquaculture system followed the same order as that of CH_4 flux. Mean fluxes at Site 1, Site 2, and Site 3 were 77.07 ± 58.79, 55.28 ± 30.89, and 43.99 ± 22.92 mg CO_2-C m^{-2} day^{-1}, respectively. The reference site showed somewhat elevated CO_2 flux compared with the aquaculture ponds (243.23 ± 206.78 mg CO_2-C m^{-2} day^{-1}) but remained significantly lower than the sewage water. The one-way ANOVA indicates that all sites, except the sewage channel, do not differ significantly.

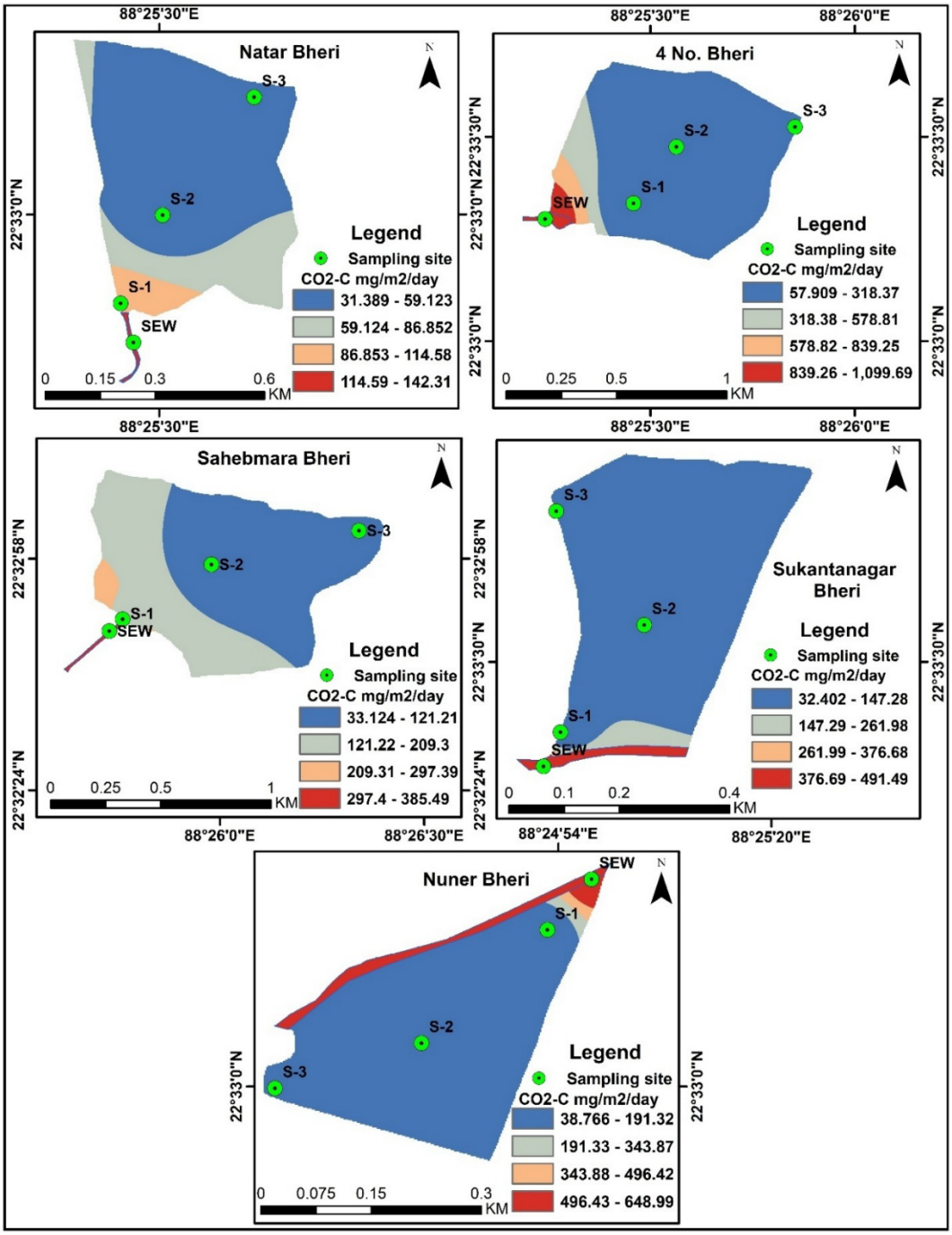
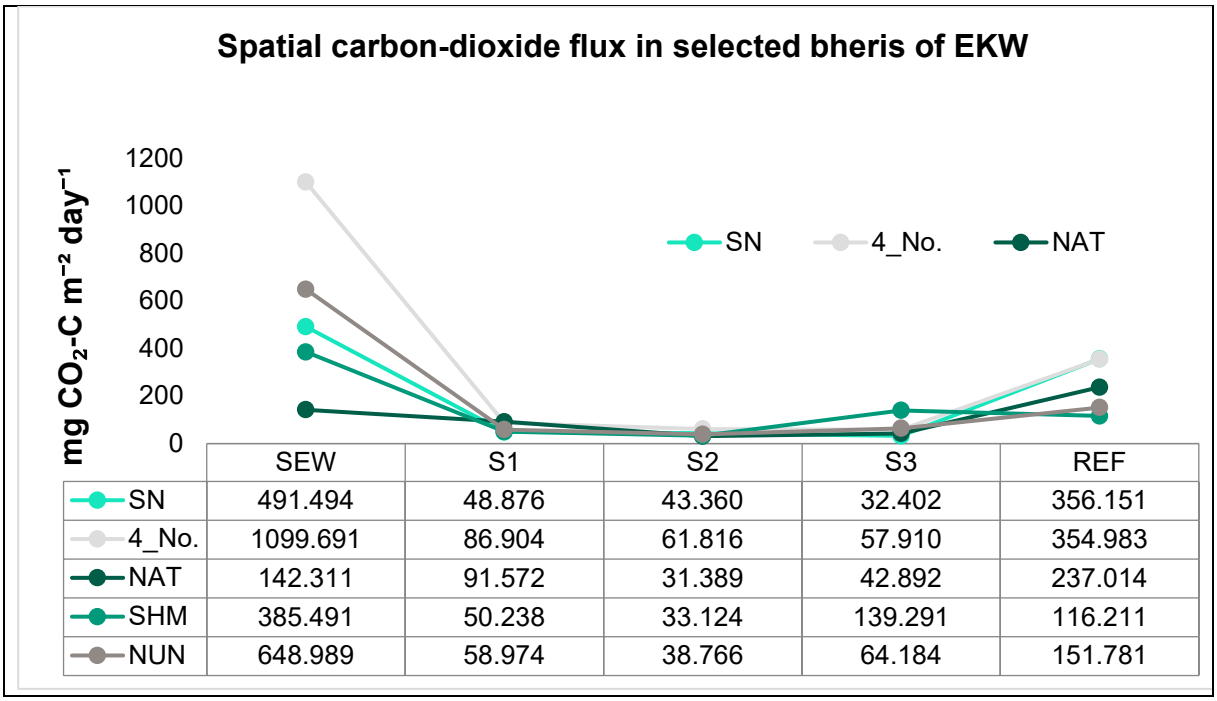


Figure 10. Spatial distribution maps of CO_2 in five *bheris* during the present study. Source: Authors



	SEW	S1	S2	S3	REF
SN	491.494	48.876	43.360	32.402	356.151
4_No.	1099.691	86.904	61.816	57.910	354.983
NAT	142.311	91.572	31.389	42.892	237.014
SHM	385.491	50.238	33.124	139.291	116.211
NUN	648.989	58.974	38.766	64.184	151.781

Figure 11. Spatial carbon-dioxide flux recorded in the selected *bheris* of EKW (SN: Sukanta Nagar *bheri*, 4.No.: 4 No. *bheri*, NAT: Natar *bheri*, SHM: Sahebmara *bheri*, and NUN: Nuner *bheri*). Source: Authors

3.1.3 Nitrous oxide (N_2O) flux

Nitrous oxide emissions were consistently low across all sites, with limited spatial variation (Figs. 11 and 12). N_2O fluxes ranged from 0.011 to 0.249 mg N_2O-N m^{-2} day^{-1}, and mean values varied only slightly among the studied sites: 0.048 ± 0.03 mg N_2O-N m^{-2} day^{-1} at S1, 0.053 ± 0.04 mg N_2O-N m^{-2} day^{-1} at S2, 0.048 ± 0.03 mg N_2O-N m^{-2} day^{-1} at S3, 0.049 ± 0.04 mg N_2O-N m^{-2} day^{-1} at the SEW (Sewage channel), and 0.082 ± 0.06 mg N_2O-N m^{-2} day^{-1} at the reference site. Statistically significant spatiotemporal differences in N_2O flux were not observed among the sampling sites in the EKW during the present study period (Table 1). This shows that, unlike CH_4 and CO_2, the N_2O flux remained relatively stable throughout EKW during the study period. It should be noted that the wastewater entering these sewage-fed *bheris* is only partially treated prior to discharge. The consistently low N_2O fluxes are likely linked to the predominantly anaerobic conditions prevailing in these systems, which tend to favour the complete reduction of nitrogen to N_2 rather than its release as NO. This contrast between the strongly gradient-driven carbon gases and the spatially uniform nitrous oxide is examined further in relation to the water- and sediment-quality drivers considered in Section 3.2.

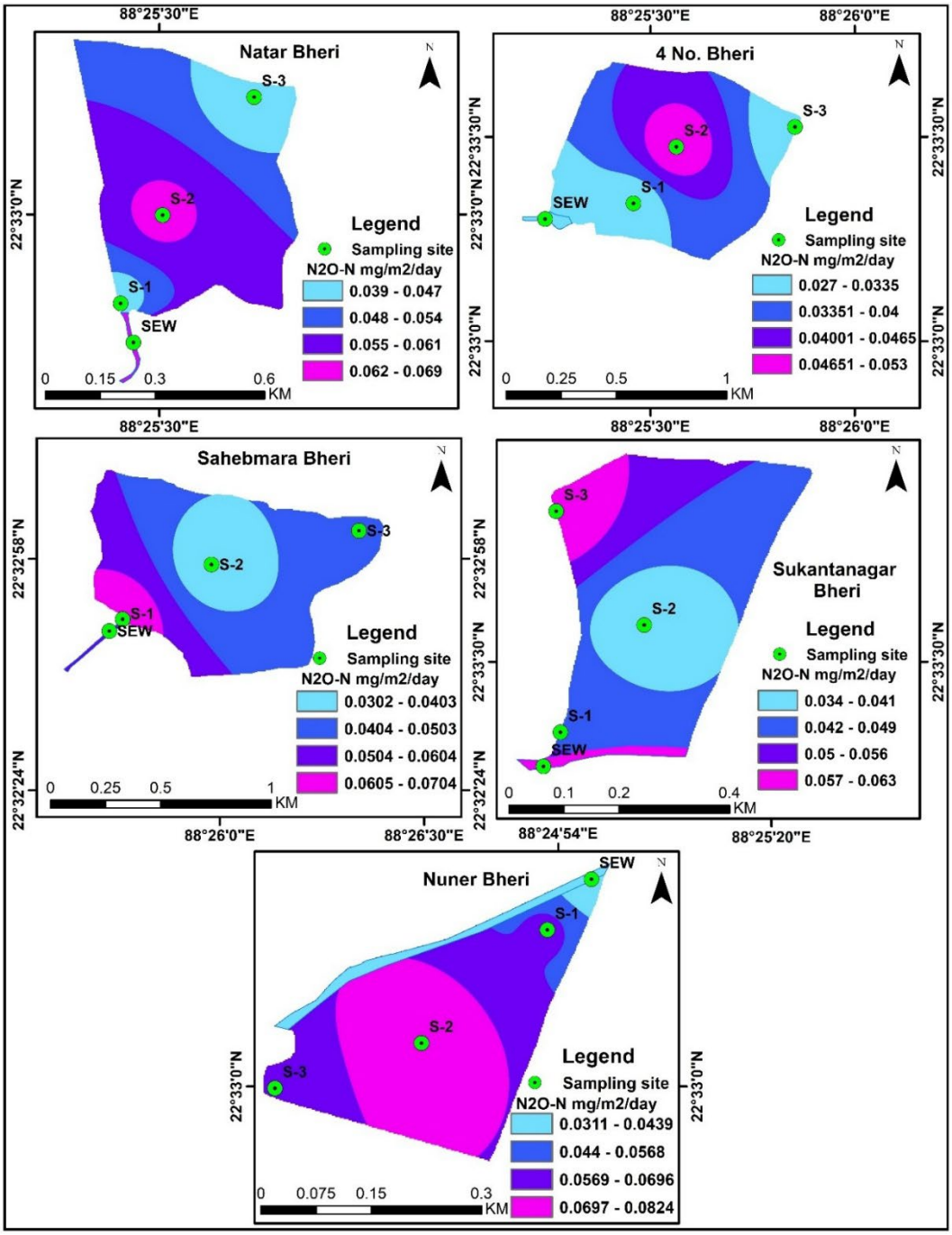
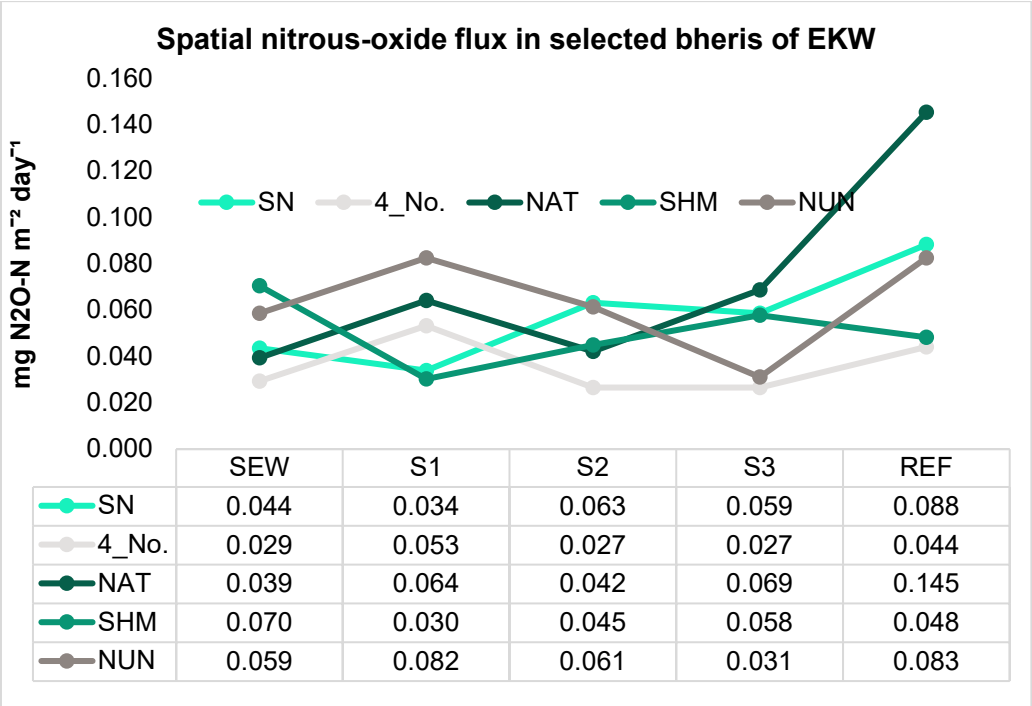


Figure 12. Spatial distribution maps of N_2O in five *bheris* during the present study. Source: Authors



	SEW	S1	S2	S3	REF
SN	0.044	0.034	0.063	0.059	0.088
4_No.	0.029	0.053	0.027	0.027	0.044
NAT	0.039	0.064	0.042	0.069	0.145
SHM	0.070	0.030	0.045	0.058	0.048
NUN	0.059	0.082	0.061	0.031	0.083

Figure 13. Spatial nitrous-oxide flux recorded in the selected *bheris* of EKW (SN: Sukanta Nagar *bheri*, 4.No.: 4 No. *bheri*, NAT: Natar *bheri*, SHM: Sahebmara *bheri*, and NUN: Nuner *bheri*). Source: Authors.

3.1.4 Water quality parameters

Water quality parameters and air temperature measured in the five *bheris* of EKW were pooled together, and descriptive statistics of the analysed parameters in all sites and the corresponding sewage channel are presented in Table 2. The air temperature showed a wide variation (22.5 to 33.5°C) during the study period, with an average of 29.33°C. The water temperature ranged from 27.6 to 33.9°C with an average water temperature of 30.1°C. The water pH remained neutral to alkaline throughout the sampling period. The pH ranged from 6.92 to 9.94. Values of pH, EC, TDS, DO, TA, TH, TP, PO_4^{3-} differed significantly ($p < 0.05$) between sewage water and the sampling sites of the *bheris*. The range of DO level at the sewage site varied from 0 to 2.7 mg L-1 with an average of 0.26 mg L-1, well below the minimum level generally required for fish survival (3.0 mg L^{-1}). The BOD, COD and depth showed significant variation ($p< 0.05$) across all sites. The BOD concentration was recorded in the order of sewage (68.53 mg L^{-1}) > site 1 (inlet - 49.53 mg L^{-1}) > site 2 (middle – 41.53 mg L^{-1}) > site 3 (outlet – 33.87 mg L^{-1}). The COD concentration was also recorded in a similar order of sewage (126.17 mg L^{-1}) > inlet- site 1 (92.30 mg L^{-1}) > middle – site 2 (75.86 mg L^{-1}) > outlet - site 3 (61.73 mg L^{-1}). The average depth of the *bheris* varied from 45 to 120 cm. Whereas other parameters, such as transparency, Chl a, water temperature, air temperature, turbidity, and nitrate, showed no significant differences across all the sampling sites in the *bheris*. Chl-*a* concentration ranged from 59.91 to 372.82 mg m^{-3}, with site 2 having the highest value (234.35 mg m^{-3}) and site 1 having the lowest (189.15 mg m^{-3}). Transparency ranged from 6.6 to 28.0 cm, with the maximum Secchi disc transparency (28 cm) recorded at site 3.

Table 2. Descriptive statistics of water quality parameters in selected *bheris* of EKW

Parameters	Site-1		Site-2		Site-3		Sewage	
	RANGE	MEAN±SD	RANGE	MEAN	RANGE	MEAN	RANGE	MEAN
Depth (cm)	45-105	87.33±15.37^{bc}	60-120	89.00±18.43^{c}	50-80	65.07±9.90^{a}	60-95	75.87±10.91^{ab}
Transp.(cm)	12-24.9	17.27±3.99^{a}	10-23	17.42±3.57^{a}	6.6-28	17.22±5.60^{a}	NA	NA
Temp Air (°C)	22.5-32.8	28.99±3.17^{a}	23-33	29.12±2.95^{a}	23-33.5	29.31±3.07^{a}	24-33.5	29.90±2.94^{a}
Temp Water(°C)	27.6-33.8	29.83±1.57^{a}	27.8-33.7	29.84±1.64^{a}	28-33.7	29.87±1.56^{a}	28.5-33.9	30.73±1.55^{a}
pH	7.78-9.94	8.79±0.70^{b}	7.7-9.48	8.99±0.4^{b}	7.78-9.92	8.95±0.64^{b}	6.92-9.2	7.54±0.60^{a}
Sp. cond.(µS cm^{-1})	415-1187	650.80±216.72^{a}	402-1042	592.80±160.84^{a}	409-1049	605.20±162.80^{a}	324-2350	1090.73±562.19^{b}
D.O. (mg L^{-1})	6.4-9.6	7.81±0.95^{b}	6.6-9.4	8.02±0.95^{b}	5.8-9.2	7.87±0.95^{b}	0-2.7	0.26±0.74^{a}
TDS (mg L^{-1})	294-842	459.73±153.75^{a}	284-736	420.20±113.51^{a}	290-744	428.87±115.69^{a}	230-1630	771.73±380.67^{b}
TA (mg L^{-1})	112-188	149.67±25.76^{a}	108-196	143.67±26.72^{a}	92-202	136.93±34.82^{a}	136-456	284.47±70.41^{b}
TH (mg L^{-1})	132-360	184.93±54.70^{a}	120-200	158.93±28.43^{a}	108-200	153.87±30.20^{a}	140-740	314.87±171.05^{b}
Tur (NTU)	33.1-110	64.47±24.71^{a}	32.1-104	62.57±20.70^{a}	26.8-98.7	61.01±22.44^{a}	21.5-118.4	77.18±28.44^{a}
NO_3-N (mg L^{-1})	0.02-0.05	0.03±0.01^{a}	0.013-0.06	0.02±0.02^{a}	0.02-0.09	0.03±0.02^{a}	0.011-0.187	0.05±0.05^{a}
TP (mg L^{-1})	0.12-0.86	0.32±0.21^{a}	0.11-0.76	0.31±0.19^{a}	0.08-0.60	0.29±0.16^{a}	0.12-5.22	1.29±1.44^{b}
PO_4-P (mg L^{-1})	0.02-0.65	0.16±0.16^{a}	0.01-0.65	0.13±0.16^{a}	0.01-0.46	0.11±0.12^{a}	0.05-1.70	0.66±0.57^{b}
TN (mg L^{-1})	0.02-0.45	0.09±0.12^{a}	0.02-0.44	0.09±0.13^{a}	0.02-0.45	0.09±0.13^{a}	0.02-0.58	0.16±0.17^{a}
Chl a (mg m^{-3})	89.6-312.75	189.15±60.27^{a}	85.65-372.82	234.35±92.69^{a}	59.91-357.12	221.43±83.42^{a}	NA	NA
BOD(mg L^{-1})	36-64	49.53±8.09^{c}	32-54	41.53±5.95^{b}	26-48	33.87±5.22^{a}	50-90	68.53±13.18^{d}
COD (mg L^{-1})	68-124	92.30±17.10^{c}	60-98.28	75.86±10.70^{b}	48-84	61.73±9.04^{a}	92-168	126.17±24.31^{d}

*The same letter (superscripts) shows no significant variation between the sites and different letters indicated significant difference between sites at 5% level of significance.

NA – Not assessed for the site during the study

3.1.5 Primary productivity

The mean values of GPP, NPP, and community respiration (CR) across the five *bheris* are presented in Fig. 14. GPP varied between 337.5 and 675 mg C m^{-3} h^{-1}, with an overall mean of 492.17 ± 114.98 mg C m^{-3} h^{-1}. NPP ranged from 125 to 500 mg C m^{-3} h^{-1} and averaged 258.83 ± 102.6 mg C m^{-3} h^{-1}. Community respiration exhibited values between 75 and 387.5 mg C m^{-3} h^{-1}, with a mean of 233.33 ± 93.14 mg C m^{-3} h^{-1}. Among the sites, 4 No. *Bheri* recorded the highest GPP; however, it simultaneously exhibited the lowest NPP relative to the other *bheris*.

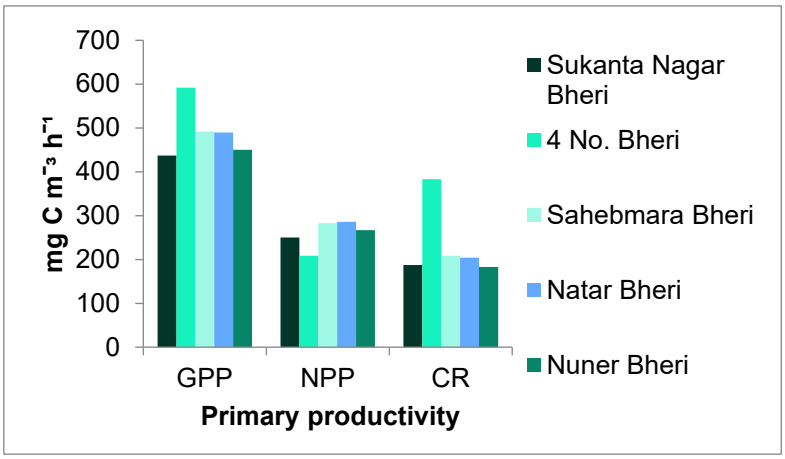


Figure 14. Gross Primary Productivity (GPP), Net Primary Productivity (NPP) and Community Respiration (CR) recorded in five *bheris*. Source: Authors

3.1.6 Trophic State Index

The CTSI values calculated for the five *bheris* of the EKW (Table 3) showed consistently high trophic levels across the study sites. All *bheris* fell within the range of 80.36 to 91.39, indicating hyper-eutrophic conditions (Table 3). Among the sites, Sukanta Nagar *Bheri* exhibited CTSI values between 80.53 and 89.40, with a mean of 83.33 ± 3.15, while 4 No. *Bheri* recorded a slightly higher mean CTSI (84.55 ± 3.07), ranging from 81.11 to 88.89. Natar *Bheri* and Sahebmara *Bheri* showed comparatively narrower ranges (80.44-91.20 and 80.36-84.97), with mean values of 83.22 ± 3.88 and 82.58 ± 1.60, respectively. Nuner *Bheri* presented CTSI values between 84.35 and 91.39, yielding the highest mean among all *bheris* (87.96 ± 2.51). These values collectively confirm that the wastewater-fed aquaculture system in EKW is characterised by elevated nutrient concentrations and high algal productivity.

Table 3. Carlson Trophic State Index (CTSI) values in selected *bheris* of East Kolkata Wetlands (EKW)

Bheris	Carlson Trophic State Index (CTSI)	
	Range	Mean ± SD
Sukanta Nagar *Bheri*	80.53 - 89.40	83.33 ± 3.15
4 No. *Bheri*	81.11 - 88.89	84.55 ± 3.07
Natar *Bheri*	80.44 - 91.20	83.22 ± 3.88
Sahebmara *Bheri*	80.36 - 84.97	82.58 ± 1.60
Nuner *Bheri*	84.35 - 91.39	87.96 ± 2.51

3.1.7 Correlation of GHGs and water quality parameters

Fig. 15 presents Spearman's rank correlation coefficients between GHG fluxes and water quality parameters estimated in the five *bheris* of EKW. It was observed that CH_4 had a significant strong positive correlation with CO_2 (p<0.001, r = 0.56), both CH_4 and CO_2 had a significant strong positive correlation with BOD (p<0.001, r = 0.62, r = 0.57), COD (p<0.001, r = 0.60, r = 0.53) and significant strong negative correlation with pH (p<0.001, r = -0.43, r = -0.55) and DO (p<0.001, r = -0.45, r = -0.47). CH_4 had a significant positive correlation with TA (p<0.01, r = 0.37), TH (p<0.01, r = 0.37) and a positive correlation with TN (p<0.05, r = 0.30). CO_2 gas had a strong significant positive

correlation with TH (p<0.001, r = 0.58) and significant positive correlation with EC (p<0.01, r = 0.53), TDS (p<0.01, r = 0.57), TUR (p<0.01, r = 0.56), PO_4^{3-} (p<0.01, r = 0.54) and positive correlation with TP (p<0.05, r = 0.49) and TA (p<0.05, r = 0.47). N_2O gas had a positive correlation with DO (p<0.05, r = 0.32).

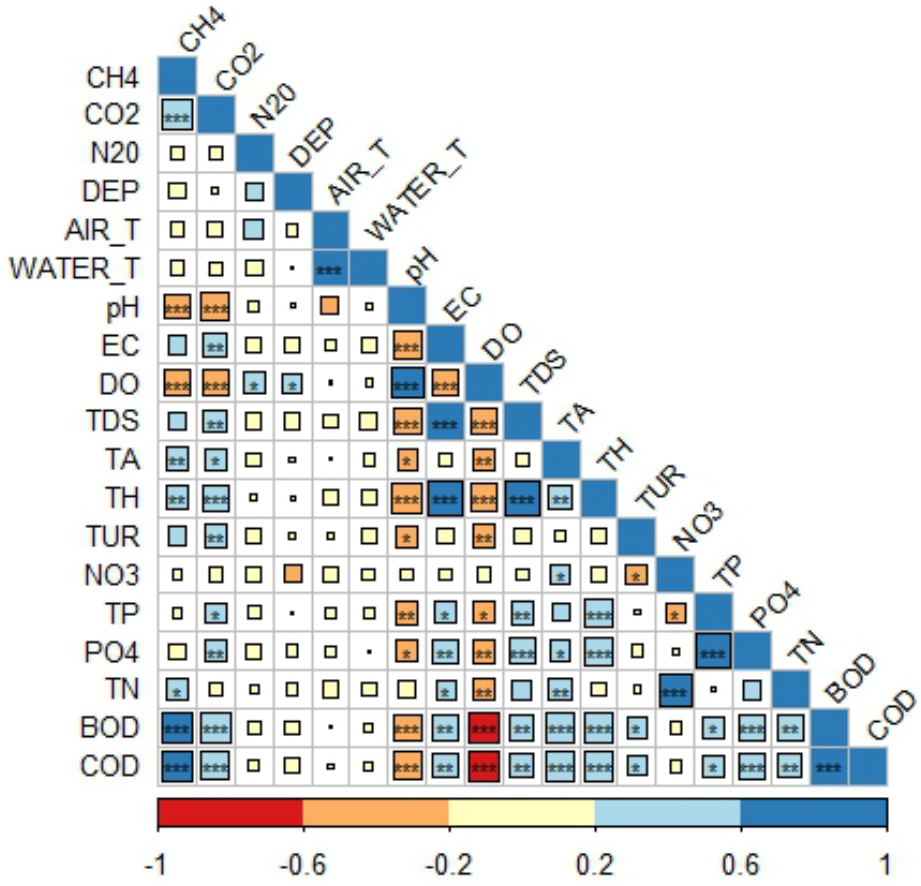


Figure 15. Spearman's rank correlation of physiochemical water quality parameters and greenhouse gases (GHGs) across five selected *bheris* of EKW.
Source: Authors

Note: The lower triangular matrix presents Spearman's rank correlation coefficients (ρ) between greenhouse gases (CH_4, CO_2 and N_2O) and physicochemical water quality parameters. The colour gradient represents the direction and strength of correlations, ranging from −1 (perfect negative correlation; red) to +1 (perfect positive correlation; dark blue), with pale yellow indicating weak or negligible correlations. The size of the squares within each cell is proportional to the absolute magnitude of the correlation coefficient, with larger squares representing stronger correlations. Statistical significance is indicated by asterisks: ***p* < 0.05 (*), *p* < 0.01 (**), and *p* < 0.001 (***)**. Cells without asterisks indicate statistically non-significant correlations ($p \geq 0.05$).

Abbreviations: CH_4 = methane; CO_2 = carbon dioxide; N_2O = nitrous oxide; DEP = water depth; AIR_T = air temperature; WATER_T = water temperature; pH = potential of hydrogen; EC = electrical conductivity; DO = dissolved oxygen; TDS = total dissolved solids; TA = total alkalinity; TH = total hardness; ORP = oxidation–reduction potential; TUR = turbidity; NO_3 = nitrate; TP = total phosphorus; PO_4 = phosphate; TN = total nitrogen; BOD = biochemical oxygen demand; COD = chemical oxygen demand.

3.1.8 Sediments quality parameters

Sediment quality parameters such as pH, electrical conductivity (mS cm^{-1}), organic carbon (%), soil texture, available nitrogen (mg $100g^{-1}$), total nitrogen (%), available phosphorus (mg $100g^{-1}$), and TP (mg $100g^{-1}$), were recorded at the three sites in the five sewage-fed *bheris* of EKW during the study period. The mean value at site-1 (inlet), site-2 (midpoint) and site-3 (outlet) of five sewage-fed *bheris* are presented in Table 4. One-way ANOVA shows that there is no significant spatiotemporal difference observed in the analysed parameters, except for total phosphorus, where site 1 significantly varied (p< 0.05) from other sites. Collectively, these gaseous, water-column and sediment results are interpreted in an integrated manner in the following section.

Table 4. Sediment quality parameters in selected *bheris* of EKW

Site	Site-1		Site-2		Site-3	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
pH	7.23-7.66	7.42±0.13[a]	7.12-7.64	7.39±0.17[a]	7.12-7.61	7.35±0.17[a]
EC (mS cm^{-1})	1.58-2.67	1.92±0.36[a]	1.36-2.54	1.82±0.37[a]	1.47-2.51	1.82±0.36[a]
OC (%)	3.15-5.84	4.38±1.04[a]	2.13-6.12	4.01±1.30[a]	2.32-5.89	3.44±1.05[a]
Sand (%)	50-89.5	69.89±15.03[a]	65-87.50	76.06±8.15[a]	49-88.50	70.72±16.57[a]
Silt (%)	8-39	22.72±11.30[a]	9-26	17.28±6.12[a]	8.50-42	22.89±14.04[a]
Clay (%)	2.5-12	7.50±4.44[a]	3.50-9	6.89±2[a]	3-11	6.39±3.04[a]
Av. P (mg $100g^{-1}$)	4.1-13.4	8.52±3.75[a]	3.42-15.21	7.55±4.06[a]	3.11-15.87	8.27±5.19[a]
Total P (mg $100g^{-1}$)	18.62-31.23	26.49±4.99[b]	17.85-26.15	21.21±3.07[a]	17.45-23.78	21.47±2.11[a]
Av. N (mg $100g^{-1}$)	27.21-57.98	39.66±10.32[a]	28.66-89.35	42.92±26.13[a]	29.33-49.88	34.93±8.16[a]
Total N (%)	0.35-1.39	0.79±0.29[a]	0.41-0.95	0.65±0.19[a]	0.42-0.93	0.59±0.20[a]

*The same letter (superscripts) shows no significant variation between the sites, and different letters indicate a significant difference between sites at 5% level of significance.

3.2 Discussion

This section interprets the results in an integrated manner. It first considers the spatial patterns of greenhouse-gas emissions and their proximate controls, then relates these to the water- and sediment-quality gradients, primary productivity and trophic status of the *bheris*, and finally synthesises the biogeochemical linkages and their wider climate significance. Throughout, the sewage-to-outlet gradient provides a unifying thread that connects the individual findings.

3.2.1 Greenhouse Gas Emissions

The present study demonstrates clear spatial contrasts in greenhouse gas emissions across the sewage channel, aquaculture *bheris* and the reference upland site within the EKW. CH_4 and CO_2 fluxes were strongly site-dependent, whereas N_2O showed limited variability. These patterns highlight the influence of sewage loading, organic matter availability and pond hydrodynamics on carbon cycling within this unique wastewater-fed aquaculture landscape.

CH_4 fluxes were markedly higher in the sewage channel than in the *bheris* and the reference site, reflecting the high organic load and persistent reducing conditions typical of raw sewage environments. Such elevated CH_4 production aligns with observations from other sewage-fed or hypereutrophic systems, where methanogenesis is enhanced by abundant labile substrates and strong anoxia (Conrad, 2020). The gradual decline in CH_4 emissions from Site 1 (inlet) to Site 3 (outlet) suggests progressive organic matter mineralisation and improved oxygen availability along the flow path, a pattern also reported from aquaculture ponds with well-maintained dissolved oxygen and properly managed ponds (Yang et al., 2025). The relatively low CH_4 flux at the reference upland site reflects lower organic inputs and more oxic sediment conditions, consistent with earlier wetland studies that documented strong substrate control over methanogenic activity (Segers, 1998).

CO_2 emissions followed the same spatial pattern as CH_4, with the sewage channel acting as the principal source. The substantially higher CO_2 flux in this zone most likely reflects intensified microbial respiration driven by large inputs of labile organic matter; such organic loading accelerates both aerobic decomposition at the water-sediment interface and anaerobic mineralisation in subsurface sediments, thereby increasing CO_2 release to the atmosphere (Jahangir et al., 2016; Yin et al., 2023). In the aquaculture *bheris*, CO_2 emissions were moderate and followed the same spatial order as methane, indicating that both gases are influenced by shared biogeochemical drivers such as sediment oxygen demand, organic loading, and microbial respiration. The comparatively higher CO_2 flux observed at the reference site may be linked to stronger sediment oxidation or shifts in the balance between autotrophic uptake and heterotrophic respiration. Similar patterns have been noted in wetland systems where carbon mineralisation and microbial respiration dominate under more oxic conditions, leading to elevated CO_2 release relative to adjacent aquatic habitats (Jahangir et al., 2016; Yin et al., 2023). The significant difference observed between the sewage channel and all other sites underscores the role of untreated wastewater inputs in intensifying carbon turnover within EKW.

N_2O fluxes remained low and showed no significant spatio-temporal variation across the study area. This behaviour is consistent with N_2O production in systems where either complete denitrification to N_2 is favoured or nitrate

availability remains limited (Butterbach-Bahl et al., 2013). The low fluxes recorded in EKW resemble those observed in other tropical wetlands and aquaculture settings, where strong reducing conditions or rapid nitrate consumption suppress N_2O accumulation (Zhou et al., 2018). Unlike CH_4 and CO_2, the N_2O emissions appeared relatively insensitive to differences in sewage load or *bheri* position, suggesting that nitrogen cycling pathways in these ponds may be more stable than carbon pathways, at least under the environmental conditions prevailing during the study period.

Overall, the study highlights that carbon-based greenhouse gases in EKW are strongly shaped by sewage-driven organic enrichment, while N_2O remains comparatively subdued. Given the global significance of wastewater-fed wetlands in carbon cycling and their expanding use in peri-urban aquaculture, understanding these emission patterns is essential for balancing food production with climate mitigation.

3.2.2 Water quality parameters

The physicochemical characteristics measured across the five *bheris* of the EKW reveal distinct spatial patterns shaped by the continuous inflow of domestic sewage and the progressive transformation of wastewater along the inlet–middle–outlet gradient. The wide variation in air and water temperature during the study period is consistent with seasonal fluctuations typical of shallow tropical wetlands, where limited water depth allows sunlight penetration, facilitating algal growth (Khan et al., 2024). Water temperatures remained within the upper thermal tolerance limits for warm-water aquaculture species commonly cultured in the EKW, although elevated temperatures can accelerate microbial respiration and organic matter decomposition (Cao et al., 2025).

The pH values, which remained neutral to alkaline, are a critical factor that shapes the structure of the periphytic algae community and key determinants for the growth of these organisms, as they modulate the efficiency of their photosynthetic processes (Kunyu et al. 2024; Mirzahasanlou et al., 2020, Tang et al., 2025). Significant spatial differences in pH, EC, TDS, DO, alkalinity, hardness, redox potential and phosphorus fractions indicate strong physicochemical gradients between the sewage channel and the *bheris*. These variations can be attributed to the differential rates of dilution, nutrient assimilation, sediment-water interactions, and biological uptake occurring along the flow path (Khan et al., 2024).

Dissolved oxygen concentrations were particularly low at the sewage entry point, with values frequently below 1 mg L^{-1}. Such hypoxic to anoxic conditions are typical of untreated wastewater channels and have been reported in earlier studies from the EKW (Khan et al., 2024). DO values increased modestly towards the outlet, reflecting the combined effects of aeration and algal photosynthesis within the *bheris*. However, persistently low DO in some locations remains a concern for fish survival, as concentrations below 3 mg L^{-1} can cause stress for aquatic life (Ali and Mishra, 2022).

BOD and COD exhibited a clear decreasing trend from the sewage channel to the outlet, demonstrating the sewage retention and treatment function of the *bheris* as an aquaculture pond. Similar attenuation patterns have been reported in studies examining the purification efficiency of EKW wastewater-fed fisheries, where microbial degradation and sedimentation substantially reduce organic loads along the treatment pathway (Mukherjee and Dutta, 2016). The high BOD and COD in the inlet zone reflect the substantial organic loading received from the Kolkata metropolitan wastewater network, whereas the gradual reduction downstream highlights the role of the *bheris* as efficient bioreactors supporting both aquaculture and wastewater remediation.

The measured depth variation (45-120 cm) aligns with the typical shallow morphology of EKW *bheris*, which enhances nutrient recycling and sediment resuspension (Jan et al., 2025). The lack of significant differences in transparency, chlorophyll *a*, turbidity, and nitrate across the sites suggests that phytoplankton biomass and suspended solids remained broadly similar within the *bheris*. Nonetheless, elevated Chl-a concentrations, particularly at the mid-point site (S2), reflect high primary productivity driven by nutrient-rich inflows, a well-documented feature of sewage-fed aquaculture systems (Bunting et al., 2010).

The low transparency values recorded (6.6-28.0 cm) are typical of eutrophic, sewage-influenced wetlands where dense phytoplankton blooms and suspended particulate matter limit water clarity (Khan & Ansari, 2005). Despite this, primary productivity remains high due to nutrient availability and shallow water depth, supporting the growth of planktonic food webs essential for carp-based fisheries in the EKW.

Overall, the observed physicochemical patterns support the interpretation that the EKW *bheris* function as dynamic biogeochemical units in which wastewater transformation, nutrient cycling, and aquaculture production occur simultaneously. The spatial gradients in organic matter load, DO, pH, and nutrient levels reflect the sequential

remediation process characteristic of wastewater-fed wetlands and emphasise the ecological significance of the EKW as a multifunctional system that provides both livelihood and environmental services.

GPP and NPP depend on nutrient content and other factors, such as light and temperature. Similar values of GPP and NPP were reported in *bheris* of the EKW by Saha et al. (2016). NPP is the rate at which organic molecules and biomass are produced by the plant or ecosystem, which can be regarded as a gauge of the net ecosystem productivity that sustains fish production (Saha et al., 2016). High GPP and CR were observed in the studied *bheris* during the study period; however, NPP was relatively low because more of the carbon fixed by photosynthesis is consumed by respiration before it can be stored as biomass. A study of floodplain lake systems showed that dominant phytoplankton groups had high gross primary production (GPP) but lower NPP**,** because much of the fixed carbon was respired rather than stored or exported. Water levels, strong light, and nutrient interactions influenced both GPP and respiration, affecting the overall carbon balance (Jia et al., 2022).

3.2.3 Trophic State Index

The trophic state indices values recorded across the five *bheris* of the EKW indicate consistently eutrophic to hypereutrophic conditions, reflecting the influence of continuous wastewater inputs on water quality and primary productivity. Similar patterns have been reported in earlier assessments of EKW, where nutrient-rich sewage inflows were shown to support high phytoplankton biomass and reduced water transparency (Bunting et al., 2010). The elevated CTSI values observed in this study are also consistent with broader research on wastewater-influenced wetlands, which often exhibit elevated nutrient concentrations and strong algal responses due to sustained external loading and internal recycling processes (Jahangir et al., 2016).

The consistently high trophic state across the system underscores both the productivity and vulnerability of EKW's wastewater-fed aquaculture landscape. While nutrient enrichment supports fish production, it also increases the risk of algal blooms and oxygen stress, which can influence ecosystem functioning and biogeochemical dynamics.

3.2.4 Relationship of GHGs and water quality parameters

The correlation patterns observed between greenhouse gases and water quality parameters across the five *bheris* of the EKW provide important insights into the biogeochemical controls governing carbon and nitrogen cycling in these sewage-fed aquaculture systems. The strong positive association between CH_4 and CO_2 suggests a common origin related to organic matter mineralization (Friese et al., 2021; He et al., 2022), where simultaneous aerobic and anaerobic microbial processes contribute to gas production. Similar coupling between CH_4 and CO_2 has been reported in nutrient-rich tropical wetlands and aquaculture ponds, where sustained organic loading enhances both heterotrophic respiration and methanogenesis (Purvaja & Ramesh, 2001).

The positive correlations of CH_4 and CO_2 with BOD and COD further support the central role of organic enrichment in regulating GHG emissions. High BOD and COD reflect intensified microbial degradation of organic substrates, which enhances CO_2 production in oxic zones and promotes CH_4 formation in oxygen-depleted zones. This relationship is widely documented in wastewater-fed wetlands and fishponds with high organic throughput (Bastviken et al., 2004). The strong negative correlations of both gases with pH and DO indicate that acidic and low-oxygen conditions favour anaerobic processes. Lower pH shifts the carbonate equilibrium towards dissolved free CO_2 and favours its evasion to the atmosphere, while reduced DO levels restrict aerobic respiration and support methanogenic pathways (Yvon-Durocher et al., 2014; Conrad, 2020).

The significant positive relationships between CH_4 and variables such as alkalinity, hardness, and TN suggest that ionic strength, moderate redox fluctuations, and nutrient enrichment contribute to conditions conducive to CH_4 production. Redox stratification, common in shallow, organic-rich wetlands, facilitates transitions between oxidised and reduced states that favour methanogenic activity, as reported in tropical floodplain and constructed wetlands (Zhang et al., 2025). The association with TN may reflect indirect stimulation of methanogenesis via increased primary productivity and subsequent deposition of labile organic matter.

For CO_2, positive correlations with EC, TDS, turbidity and phosphorus fractions (PO_4^{3-} and TP) indicate that solute-rich, eutrophic conditions enhance mineralization processes. Elevated turbidity and nutrient levels characterize the EKW *bheris* due to continual wastewater inflow, promoting high phytoplankton biomass and rapid decomposition, ultimately increasing CO_2 release. Comparable relationships between phosphorus loading and CO_2 efflux have been reported in rivers (Upadhyay et al., 2023), and a contradictory finding of negative correlation of TDS with CO_2 is reported by Hao et al. (2021).

Unlike CH_4 and CO_2, the N_2O showed only a modest positive correlation with DO, suggesting that nitrification processes dominate N_2O production in these systems. Under oxygenated but variable DO conditions, ammonia-oxidising microorganisms generate N_2O as an intermediate or by-product, a trend observed widely in water bodies (Wang et al., 2025). The absence of strong correlations with nitrogen species suggests that oxygen availability, rather than nitrogen concentration, exerts greater control over N_2O dynamics in the EKW *bheris*.

Collectively, these results highlight the sensitivity of GHG emissions in sewage-fed aquaculture wetlands to organic matter load, oxygen dynamics, and nutrient status. The findings align with global assessments indicating that tropical wetlands receiving anthropogenic inputs often serve as significant sources of CH_4 and CO_2 due to enhanced microbial respiration and reduced sedimentation (Rosentreter et al., 2021). Understanding these relationships is crucial for designing emission-mitigation strategies within multifunctional wetland-aquaculture systems such as the EKW.

3.2.5 Physicochemical parameters of sediments

Soil is a critical component of the aquatic environment, not only holding water for aquatic animals but also providing nutrients essential to biological productivity (Saha, 2003). The exchange of nutrients from bottom soil to the overlying water is influenced by factors such as temperature, pH, and nutrient concentrations in the water (Miranda et al., 2021). The pH value of sediment at different study sites of EKW during the study period ranged from 7.12 to 7.66 which is within a neutral to slightly alkaline range, supporting the productivity of aquatic ecosystems by fostering diverse microbial and plankton communities essential for nutrient cycling and primary production, which also influences GHGs emission by enhancing processes such as methanogenesis and ammonia volatilization (Saha et al., 2016). The trend in sediment EC was similar to that of pH, with the highest and lowest EC values at Site 1 (1.58-2.67 mS cm^{-1}) and Site 3 (1.47-2.51 mS cm^{-1}), respectively. EC measurements can help characterize soil texture, particle size distribution, and chemical properties, which are critical for wetland restoration and management by identifying features like clay content and aquitards that affect water retention and flow (Emmanuel et al., 2023). Changes in EC can also indicate clogging in constructed wetlands, as variations relate to substrate composition and pollutant concentrations, making it a useful tool for monitoring wetland health and treatment efficiency (Wang et al., 2021). Das et al. (2024) reported moderately fine-textured sediments of the sandy clay loam class in Gangetic floodplain wetlands of West Bengal. In the present study, texture analysis revealed sandy loam type sediment with maximum sand and silt fractions at Site 1 and Site 3, respectively. The mean value of sand, clay and silt at site-1 (inlet), site-2 (midpoint) and site-3 (outlet) of five sewage-fed ponds are presented in Table 4. The distribution of sand, silt and clay was in the ranges of 49-89%, 8-42% and 3-11%, respectively. Mukherjee et al. (2022) reported in their study in EKW that the sand, clay and silt were in the ranges of 25-65%, 27-70% and 18-55%, respectively, which shows the silty clay type soil. Sediment texture affects sediment permeability, nutrient retention, and contaminant binding, which are critical for pond water quality and ecological function (Gupta et al., 2016).

3.2.6 Sediment organic carbon and nutrient contents

Organic carbon (%) varied from 2.13% to 6.12% at different sites in the five sewage-fed ponds, which was largely different from the findings (0.82-2.0%) of Mukherjee et al. (2022). The mean values of OC (%) in the sediment in site 1, site 2 and site 3 were 4.38±1.04%, 4.01±1.30% and 3.44±1.05% respectively, with the highest at site 1 (inlet). The accumulation of OC at this location appears to result from substantial sewage inflow through the inlet, coupled with high biomass of macrophytes and associated aquatic fauna (Zhao et al., 2015). The concentrations of TN in the five *bheris* of EKW sediment at different sites varied from 0.35-1.39%, 0.41-0.95% and 0.42-0.93%, which is notably higher than the findings (0.09-0.21%) of Mukherjee et al. (2022). The values of TN (%) decrease from inlet to outlet of the sewage-fed ponds. The values of available-N range from 27.21 to 57.98, 28.66 to 89.35 and 29.33 to 49.88 mg 100 g^{-1} at site 1, site 2 and site 3, respectively, indicating nitrogen transformation and uptake within the ponds. Sediment nitrogen dynamics in sewage-fed ponds are influenced by sewage inflow, hydrodynamics, and microbial activity, leading to spatial gradients in TN and available nitrogen concentrations (Wang et al., 2023; Zimmo et al., 2004). The concentrations of TP in the five *bheris* of EKW sediment at different sites varied from 18.62 to 31.23, 17.85-26.15 and 17.45-23.78 mg 100 g^{-1}, which is similar to the findings (0.18-0.31%) of Mukherjee et al. (2022). The values of available-P range from 4.1 to 13.4, 3.42 to 15.21 and 3.11 to 15.87 mg 100 g^{-1} at site 1, site 2 and site 3, respectively, with mean values of 8.52±3.75, 7.55±4.06 and 8.27±5.19 mg 100 g^{-1}. The slightly higher TP values recorded in the present study could be related to continued inputs of organic matter rich in phosphorus through domestic sewage and the slow recycling of sediment-bound phosphorus in these shallow, highly productive wastewater-fed ponds. Such enrichment reflects long-term accumulation of nutrients in sediment strata and underscores the role of EKW *bheris* as active nutrient sinks within the wastewater treatment-aquaculture system (Lusk & Chapman, 2021; Ding et al., 2018).

3.2.7 Greenhouse gas emissions in a global and climate-policy context

Placing the observed fluxes in a broader context provides an initial indication of their relative magnitude. The mean CH_4 flux recorded in the sewage channel (≈1175 mg CH_4 –C m^{-2} day^{-1}) lies at the upper end of values reported for eutrophic and wastewater-influenced aquatic systems, whereas fluxes within the aquaculture *bheris* (≈16–394 mg CH_4 –C m^{-2} day^{-1}) are comparable to those documented for managed freshwater ponds (MacLeod et al., 2020; Yang et al., 2025). This gradient reinforces the interpretation of the *bheris* as partial biogeochemical buffers that attenuate the extreme emissions of the raw-sewage channel. When fluxes are weighted by their global-warming potentials (approximately 27 to 30 for CH_4 and 273 for N_2O relative to CO_2 over a 100-year horizon; IPCC, 2021), methane clearly dominates the CO_2-equivalent budget of the system, a pattern consistent with the global finding that methane governs the climate forcing of inland waters (Bastviken et al., 2011; Saunois et al., 2020).

The comparatively low and spatially uniform N_2O fluxes are noteworthy given the high nitrogen loading of the incoming wastewater. This behaviour is consistent with strongly reducing conditions that favour the complete reduction of nitrate to dinitrogen rather than the release of N_2O, and with oxygen availability, rather than nitrogen concentration, acting as the proximate control on N_2O production (Hu et al., 2012; Butterbach-Bahl et al., 2013). Nevertheless, because aquaculture is projected to become an increasingly important source of N_2O globally (Williams and Crutzen, 2010; Yuan et al., 2019), even modest fluxes from systems of this spatial extent merit continued monitoring. The site-specific emission factors generated here directly address the acknowledged scarcity of data for hybrid wastewater–aquaculture systems in international inventory guidance (IPCC, 2019) and offer preliminary site-specific evidence that, once supported by year-round, wetland-wide monitoring, could contribute to the development of emission factors for such hybrid systems.

3.2.8 Implications for mitigation and management

The strong dependence of CH_4 and CO_2 emissions on organic loading and oxygen status identifies several practical levers for mitigation that need not compromise the treatment and production functions of the system. Measures that reduce the raw organic load reaching the *bheris*, such as improved primary screening and settlement of incoming sewage, or staged distribution of inflow, would be expected to lower the extreme fluxes observed in the feeder channel, the dominant hotspot. Within the ponds, management that sustains dissolved oxygen and limits sediment anoxia (for example, controlled stocking densities, periodic aeration where feasible, and management of sediment accumulation) would tend to shift carbon mineralisation towards CO_2 and away from the more potent CH_4, thereby reducing net CO_2-equivalent emissions. Because the sediments were shown to accumulate substantial organic carbon and nutrients, periodic sediment management and the beneficial reuse of nutrient-rich sediment may offer co-benefits for both emission control and pond productivity.

These options should be evaluated with explicit attention to trade-offs. Interventions that increase oxygenation or reduce organic loading may also alter nutrient recycling and primary productivity, upon which the fish yields and livelihoods supported by the EKW ultimately depend. A management strategy for the wetlands should therefore seek to optimise, rather than simply minimise, the balance between wastewater remediation, aquaculture productivity, ecosystem-service delivery, and climate mitigation, guided by continued, spatially explicit monitoring.

4. Conclusions

The present investigation provides a comprehensive assessment of GHG dynamics, water quality, trophic status, primary productivity, and sediment characteristics across sewage channels, aquaculture *bheris*, and a reference upland site within the EKW. The study clearly demonstrates strong spatial heterogeneity in CH_4 and CO_2 emissions, driven primarily by gradients in sewage-derived organic matter loading, oxygen availability, and sediment biogeochemistry, whereas N_2O fluxes remained consistently low and comparatively insensitive to site-level variation. The sewage channel emerged as the dominant hotspot of carbon emissions, reflecting intense microbial mineralisation under highly reduced conditions, while the *bheris* showed moderated fluxes indicative of progressive wastewater transformation and partial ecological buffering.

The observed physicochemical gradients, eutrophic to hypereutrophic states, and high primary productivity confirm the role of EKW *bheris* as multifunctional systems where wastewater remediation, nutrient recycling, and fish production occur simultaneously. Strong linkages between GHG emissions and parameters such as BOD, COD, DO, pH, and nutrient fractions underline the central role of organic enrichment and redox dynamics in regulating carbon cycling. Sediment analyses further revealed a substantial accumulation of organic carbon and nutrients, reinforcing the importance of sediments as long-term sinks and active regulators of biogeochemical processes.

Overall, the findings highlight that while EKW functions efficiently as a nature-based wastewater treatment and aquaculture system, the sampled sites, particularly the sewage-feeder channel, were sources of carbon-based GHGs during the study period.

4.1 Outcomes of the study

- Generated preliminary site-specific estimates of CH_4, CO_2, and N_2O fluxes from a globally significant wastewater-fed wetland-aquaculture system.
- Demonstrated clear spatial gradients in greenhouse gas emissions linked to sewage loading, and sediment-water interactions.
- Established strong relationships between GHG emissions and key water quality parameters (BOD, COD, DO, pH, nutrients), improving understanding of emission drivers in sewage-fed *bheris.*
- Confirmed persistent eutrophic to hypereutrophic conditions and high primary productivity supporting aquaculture, while simultaneously influencing biogeochemical cycling.
- Provided integrated insights into sediment texture, organic carbon, and nutrient accumulation, highlighting the role of sediments as regulators of productivity and emissions.
- Contributed baseline information to support development of management strategies that balance wastewater treatment efficiency, fish production, and climate mitigation in EKW. However, it is to be noted that the scale is limited to the northern fringes of the EKW, rather than the whole wetland system or replicating for similar systems.

4.2 Challenges and limitations

- Temporal coverage was limited to the study period and may not fully capture interannual variability or extreme events such as heatwaves, floods, or abrupt changes in sewage inflow.
- GHG flux measurements represent snapshots in time; short-term diel variability and episodic emission pulses may therefore be underestimated.
- The results are preliminary and limited to five selected *bheris* and the August–October 2025 sampling period (three sampling days per *bheri*); they should not be generalised to the wider EKW or used as wetland-wide or national estimates.
- Flux estimates are sensitive to chamber headspace volume, deployment depth and episodic ebullition; a few high values in the sewage channel strongly influence the mean.
- High spatial heterogeneity in sewage-fed systems introduces uncertainty in upscaling emissions from individual *bheris* to the entire wetland complex.

4.3 Policy relevance

The results may, in future, support the implementation of the Paris Agreement and national climate reporting obligations under the United Nations Framework Convention on Climate Change (UNFCCC). Before such use, the present preliminary estimates would need to be confirmed through longer-term, spatially representative monitoring. India's Nationally Determined Contribution (NDC) emphasizes improved waste management, climate-resilient agriculture, and enhanced carbon sinks (MoEFCC, 2022). Quantifying GHG emissions from wastewater-based aquaculture provides critical baseline information needed for incorporating managed wetlands and aquaculture systems into national GHG inventories and mitigation planning. Currently, emission factors for such hybrid systems remain poorly represented in global datasets (Saunois et al., 2020), underscoring the policy value of site-specific measurements from globally significant wetlands such as EKW.

4.4 Management and mitigation implications

The findings carry direct implications for the sustainable management of the EKW and comparable systems. Because emissions are concentrated in the raw-sewage feeder channel and scale with organic loading and oxygen depletion, targeted measures (reducing and pre-settling the incoming organic load, maintaining dissolved oxygen within the *bheris*, and managing sediment accumulation) offer the greatest scope for lowering CO_2 -equivalent emissions while preserving the treatment and production functions of the system. Given that methane dominates the climate forcing of the system, mitigation efforts that curb methanogenesis are likely to yield the largest climate benefit per unit of effort. Any intervention should, however, be assessed against its consequences for nutrient recycling, fish productivity and the livelihoods that depend on them, so that climate objectives are pursued in concert with, rather than at the expense of, the wetland's food-production and wastewater-treatment services.

4.5 Recommendations for future research

Several priorities emerge for future work: (i) year-round, higher-frequency measurements, including diel sampling, to capture the seasonal, episodic and day–night variability that snapshot campaigns cannot resolve; (ii) direct partitioning of the microbial pathways controlling CH_4 and N_2O, coupled with dissolved-gas and isotopic measurements, to strengthen mechanistic interpretation; (iii) whole-system upscaling that combines flux measurements with remote sensing and hydrological data to derive wetland-scale emission estimates and refined emission factors; and (iv) controlled evaluation of candidate mitigation measures, quantifying their effects on emissions alongside fish yield, water quality and ecosystem services. Sustained monitoring of this kind would consolidate the standing of the EKW as a globally significant reference site for understanding the climate role of wastewater-fed aquaculture.

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