Environmental Science
Advances

ROYAL SOCIETY
OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Environ. Sci.: Adv.*, 2026, **5**, 1130

Assessing the impacts of feed and species composition on greenhouse gas emission from freshwater aquaculture systems in Bangladesh

K. R. Luba,[ab] H. Rashid,[†c] M. S. Islam,[d] M. Akter,[e] R. Khatun,[a] M. Zaman[f] and M. M. R. Jahangir[*b]

Received 17th July 2025
Accepted 26th February 2026

DOI: 10.1039/d5va00215j

rsc.li/esadvances

Bangladesh, a major global aquaculture producer, is potentially a notable source of greenhouse gas (GHG) emissions from aquaculture, but no measured data have yet been reported. This study investigates hydrochemistry, dissolved GHG concentrations in water and GHG (CO_2, CH_4, and N_2O) emissions from four prevalent freshwater aquaculture systems in Mymensingh, Bangladesh, focusing on Indian major carps (IMCs), Pangasius catfish (PG), Climbing perch (CP) and Tilapia (T), along with the feed loads. Semi-structured interviews with farm managers yielded key feed input parameters, including consumption rates, protein levels, and feed conversion ratios. Dissolved GHG concentrations and atmospheric emissions were measured during 2023 to 2024 (spanning from the dry winter to the pre-monsoon season, with biweekly sampling) using the headspace extraction for dissolved gases and a 40 × 40 × 50 cm^3 acrylic floating chamber for surface fluxes, with gas chromatography. The results revealed that PG systems exhibited significantly higher CH_4, N_2O and CO_2 emissions by 89–96, 59–75 and 66–78% than IMC and T systems, likely due to intensive sinking-feed use causing low dissolved oxygen, high electrical conductivity and mineral nitrogen, thereby promoting anaerobic conditions and enhanced methanogenesis and denitrification. In contrast, the IMC and T systems, utilizing more efficient floating feeds, showed comparatively lower emissions. The dissolved gas concentration analysis further complemented the surface gas emissions data, offering a holistic understanding of emissions from aquaculture ponds. The results suggest that optimizing feed composition and management can substantially reduce the aquaculture sector's impacts on climate change. By providing a detailed understanding of the GHG emissions from different aquaculture systems, this research contributes valuable insights for policymakers, industry stakeholders, and environmental scientists.

Environmental significance

The escalating threats of global warming and climate change have become a critical concern worldwide. Apart from other industrial emissions, agricultural production significantly contributes to global GHG emissions where aquaculture is an important subsector of agriculture that has increased continuously and more than doubled globally compared to capture fisheries over the last two decades. Existing global studies often generalize aquaculture's water and air impacts, lacking specific insights into how freshwater systems contribute to emissions and how the water quality parameters correlate with the GHG production and emissions. Sustainable aquaculture growth requires balancing meeting global demand for fish with minimizing environmental footprints, particularly GHG emissions. Adopting environmentally friendly practices, such as selecting species with lower GHG emissions potential and using feeds that are efficiently digested, can significantly reduce the carbon footprint of aquaculture. This research contributes to understanding aquaculture's environmental impact and guides future strategies for sustainable aquaculture development. By focusing on feed application, a major source of emissions, and considering the impacts of unutilized feedstuff, fish waste decomposition, and aquaculture farm establishment on natural ecosystems, and water quality, this study provides critical insights into the climate footprint of aquaculture.

1 Introduction

The escalating threats of global warming and climate change have become a critical concern worldwide. Natural disasters, intensified by climate change, are growing in frequency and severity, manifesting as polar ice melting, rising sea levels, erratic rainfall, ocean acidification, tropical cyclones, forest fires, droughts, and biodiversity loss.[1] These effects are driven by increasing greenhouse gas (GHG) concentrations, which trap heat and warm the earth's lower atmosphere. Current GHG

---

[a] *Department of Environmental Science, Bangladesh Agricultural University, Mymensingh, Bangladesh*
[b] *Department of Soil Science, Bangladesh Agricultural University, Mymensingh, Bangladesh. E-mail: mmrjahangir@bau.edu.bd; Tel: +880 1719648448*
[c] *Department of Fisheries Management, Bangladesh Agricultural University, Mymensingh, Bangladesh*
[d] *Department of Environmental Science and Resource Management, Mawlana Bhashani Science and Technology University, Tangail, Bangladesh*
[e] *Soil Science Division, Bangladesh Rice Research Institute, Gazipur, Bangladesh*
[f] *Science & Agronomy, OCP Nutricrops, Morocco*

† Equally contributing first authors.

emission trends suggest that global surface temperatures may rise by 1.6–5.8 °C by the end of the century.[2] CO_2 mainly emits from burning fossil fuels and waste, while CH_4 and N_2O arise from human activities (~60%) and natural sources (~40%).[3] Major contributors include industries, energy production, agriculture, forestry, transportation, and construction.[1] Apart from other industrial emissions, agricultural production significantly contributes to global GHG emissions where aquaculture is an important subsector of agriculture that has increased continuously and more than doubled globally compared to capture fisheries over the last two decades.[4,5] Freshwater aquaculture raises aquatic animals like fish and crustaceans in freshwater habitats including ponds, lakes, and rivers[6] which contributes significantly to food security both directly (by increasing food supply and accessibility) and indirectly (as a driver of economic development).[7] In 2020, 178 million tons of fish were produced globally, of which 90 million tons were from capture fisheries and 88 million tons from aquaculture.[8] This showed a significant shift from the aquaculture share of 4% in the 1950s, 5% in the 1970s, 20% in the 1990s, and 44% in the 2010s and around 50% in 2020.[8] A modified calculation of 245 million tons of CO_2 equivalent ($MtCO_2e$) emission in 2017 represented nearly 93% of the world's aquaculture production and 0.49% of all anthropogenic GHG emissions that year.[7]

In countries like Bangladesh, where industrial GHG emissions are considered low, aquaculture can be a vital source of emission due to its high dependency and growth in this sector. Bangladesh's aquaculture production was less than a million metric tons during 2005–06, which increased to 2.64 million metric tons in 2020–21, making Bangladesh 5th in the world with aquaculture production.[5,8,9] Bangladesh's major aquaculture species are Indian major carps, exotic carp, pangasius catfish and tilapia.[10,11] A recent study conducted by Ahmed and Wahab (2018) found that the growth of the aquaculture sector in Bangladesh was driven by the development of new technologies and improved management practices, as well as by increased demand for fish from both domestic and international markets.[12] Apart from that, when it comes to GHG emissions, according to Gorsky (2019), the very small ponds comprised of only 8.6% of lakes and ponds by area globally, but they accounted for 40.6% of CH_4 and 15.1% of CO_2 emissions.[13,14] Global N_2O–N emissions from aquaculture were 9.30×10^{10} g in 2009 and were projected to rise to 3.83×10^{11} g by 2030, potentially contributing 5.72% of anthropogenic N_2O–N emissions if the sector maintains its 7.10% annual growth rate.[15] The potential of GHG production and emissions depends on numerous biotic and abiotic factors.[14,16–20] In the case of hypoxia in sediments, microorganisms create CH_4 by methanation, whereas nitrification and incomplete denitrification processes produce N_2O, which is first transported to water and then expelled to the atmosphere.[3,21–23] A study by Robb *et al.* (2017) measured GHG emissions from the culture of key aquaculture species like pangasius, Indian major carps, and tilapias. Major sources of emissions were identified to be feed application, CO_2 from soybean and feed crop cultivation, and energy use for water aeration, heating, cooling, and fish processing. Additionally, CH_4 and N_2O are released from decomposing unutilized feed and fish waste.[24]

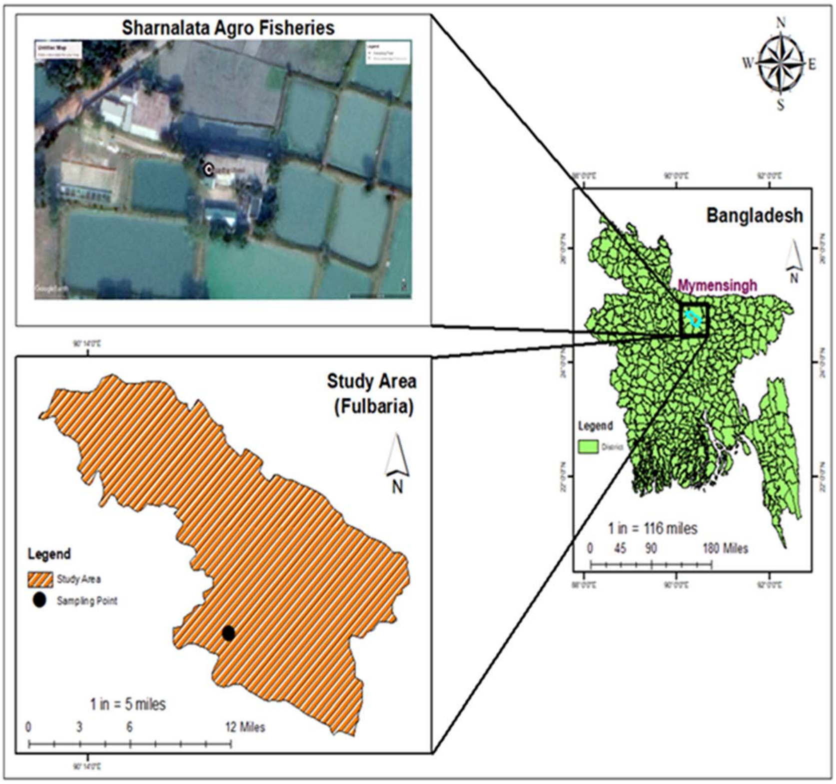

Fig. 1 Map showing the study location (sampling site) in Fulbaria, Mymensingh, Bangladesh.

Despite the rapid expansion of aquaculture in Bangladesh, the sector's contribution to GHG emissions remains underexplored. Existing global studies often generalize aquaculture's environmental impacts, lacking specific insights into how freshwater systems in Bangladesh contribute to emissions. Additionally, there is limited data quantifying the concentrations of dissolved GHG (CO_2, CH_4, and N_2O) in aquaculture systems and identifying key drivers such as feed application and unutilized feedstuff decomposition. Addressing these knowledge gaps are crucial for developing sustainable strategies for the aquaculture sector, particularly in a climate-vulnerable country like Bangladesh.

The novelty of this research lies in its integrated approach: measuring GHG emissions from key freshwater aquaculture species (pangasius, Indian major carps, climbing perch, and tilapia) while also assessing dissolved GHG concentrations in aquaculture systems. By focusing on feed application, a major source of emissions, and considering the impacts of unutilized feedstuff, fish waste decomposition, and aquaculture farm establishment on natural ecosystems, this study provides critical insights into the climate footprint of aquaculture in Bangladesh. These findings aim to support sustainable growth strategies by advancing our understanding of aquaculture's role in global GHG emissions.

2 Materials and methods

2.1 Study area

The study was conducted in a commercial fish farm in Fulbaria, Mymensingh, Bangladesh illustrated in Fig. 1. We found commercial aquaculture of Nile tilapia, Indian major carp, pangasius, exotic carps, climbing perch and native small catfishes ongoing in this farm. GHG samples were collected using a floating chamber during February to March 2023, while pond water samples were collected from a depth of 1 meter during August to September 2024. According to the "Yearbook of Fisheries Statistics of Bangladesh 2020–21" by the Department of Fisheries (DoF), Mymensingh district leads inland aquaculture in Bangladesh, producing over 0.32 million tons of fish per year, which is 15.3% of the national pond fisheries production. Pangasius catfish accounted for 46.93% of this total, with over 0.15 million tons produced.[11]

2.2 Collection of feed input data

A semi-structured interview was conducted at the required farms in the sampling site with farm managers operating pond culture systems. These interviews focused on key parameters, including pond area, stocking density, culture duration, fish production, feed consumption, feed protein content, and feed conversion ratio, as shown in Table 1. The data collected from these interviews provided valuable insights into the actual feed input requirements, feed types, and management practices prevalent in the study location. These parameters formed the basis for evaluating feed-load effects on GHG emissions and pond hydrochemistry.

2.3 Designing and construction of GHG sampling chamber

A floating chamber is a tool used to measure the flux of gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in aquatic systems. The shape of the floating chamber was cubic made of acrylic glass with attached PVC pipes for flotation (Fig. 2). The chamber was wrapped with a reflective and insulating material to reduce temperature changes inside the chamber compared to the outside atmosphere. The chamber includes a vent to allow pressure equilibration, a thermometer to measure the temperature inside the chamber, a sampling port connected with a three-way valve *via* a Teflon tube and a fan powered by a 12 V battery to assure well-mixed air during gas sampling. The chamber top was placed above the water surface while the chamber bottom is submerged in the water. After a certain period, samples were collected through the chamber top and analyzed to determine the concentration of GHGs. The chamber was designed with an open-ended bottom that can penetrate water to a depth of 10 cm, forming a seal between the water surface and the air within the chamber. The inlet and outlet of the chamber were connected with a three-way stopcock by Teflon tubing. A needle is used to collect gases through three-way valves and stored them in a pre-evacuated vial tube. A thermometer was fitted into the chamber to measure the inside temperature. The entire chamber system weight is 12 kg and easily transportable, making the measurement of gas.

2.4 Measurement of surface GHG emissions

GHGs samples were collected once a week from triplicate ponds of each species using the fabricated floating chamber and quantified with GHGs analyzer (Thermo Fisher Scientific, USA) equipped with flame ionization detector for CH_4 analysis, thermal conductivity detector for CO_2 and electron capture detector for N_2O) customized for the simultaneous analysis and suing He as a carrier gas for N_2O and N_2 for CH_4. The samples were collected at a height of 20 cm from the surface of the water at different time intervals in an exetainer (Labco Wycom, UK). Gas samples were taken in a 60 mL plastic syringe (BD Plastic)

Table 1 Fish culture systems, species composition and production data

Pond culture system	Pond area (decimal)	Stocking density (per decimal)	Culture days	Fish production (kg per decimal)	Amount of feed used (kg per decimal)	Fish feed protein (%)	Feed conversion ratio (FCR)
Nile tilapia	43.6	200	180	45	63	24%	1.4
Pangasius catfish	37	250	330	355	887	22%	2.5
Climbing perch	40	120	120	20	50	22%	1.5
Indian major carp	40	40	420	43	107	24%	2.5

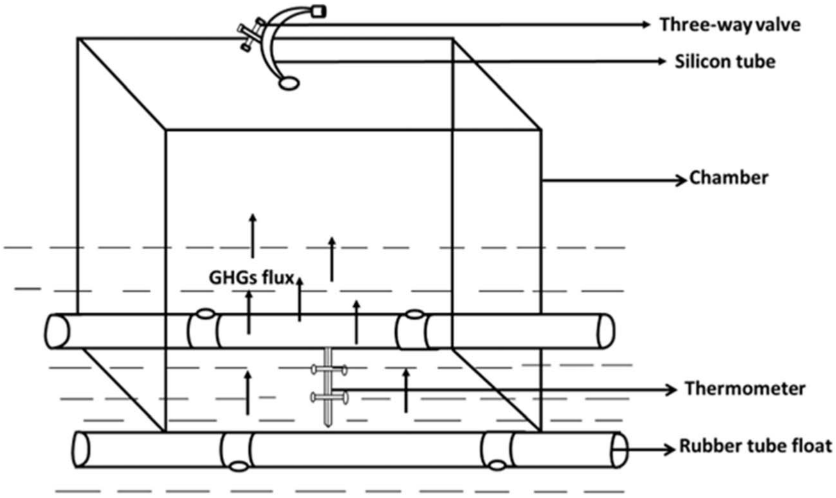

Fig. 2 Floating chamber on aquaculture pond.

equipped with a 25-gauge Luer lock needle put into a three-way stopper and a Teflon tubing attached to the chamber. A 16 mL sample was collected from the floating chamber and injected immediately into a 12 mL pre-evacuated exetainer. Each pond is allowed to take three samples. A time sequence of GHG samples usually followed three times respectively 0 minutes, 30 minutes and 1 hour time periods, enables flux gradients of these gases to be estimated in kg ha^{-1} day^{-1}. Samples were analyzed at the Department of Soil Science at Bangladesh Agricultural University according to international standard analytical procedures. Standard gases for N_2O and CH_4 (Thermo Fisher Scientific) were used to calculate the gas concentrations in the sample and after analysis of every ten samples a quality control sample for both CH_4 and N_2O was run. The calibration curve and the quality control samples confirmed the accuracy of the analysis and measurement. The specific formula for the estimations is listed below.

$$\text{Flux} = \frac{d_{\text{Gas}}}{dt} \times \frac{V_{\text{chamber}} \times p \times 100 \times \text{MW}}{R \times T} \times 10^{3\times\,\frac{1}{A}}$$

where d_{Gas} in ppb is the concentration change over time; 10^3 is the unit conversion factor; V_{chamber} is the volume of the chamber used; p is atmospheric pressure in Pa (100 is to convert Pa to hPa); MW is the molecular weight of CO_2, CH_4, N_2O; R is gas constant 8.314 J mol^{-1} K^{-1}; T is the temperature in Kelvin; A is the area of the chamber.[25]

2.5 Water sample collection and analysis

To accurately assess water quality parameters essential for optimal fish culture, the HANNA HI98194 Waterproof Portable Multiparameter probe was used (HANNA, Rumania). The probe was calibrated each time before it was used on site in the field. This advanced instrument enabled precise measurements of pH, electrical conductivity (EC), temperature, and dissolved oxygen (DO) levels, providing valuable data for understanding and managing the pond environment. In addition, in terms of ammonium and nitrate concentrations in the water samples, the classic Kjeldahl nitrogen determination procedure was adopted, utilizing the FoodALYT D 2000 distillation unit. This well-established method involves a digestion process using sulfuric acid and a catalyst to convert ammonium nitrate into ammonium sulfate. Subsequently, the FoodALYT D 2000 efficiently distilled the liberated ammonia gas, which is then absorbed into a boric acid solution. Finally, the absorbed ammonia is titrated with a standard acid solution to determine its concentration, thereby quantifying the original ammonium and nitrate content. Organic carbon of the samples was determined by wet oxidation method as outlined by Walkey and Black (1934).[26] The wet oxidation method was done with 2 mL of sample water and 1 N $K_2Cr_2O_7$ in presence of concentrated H_2SO_4, concentrated H_3PO_4 and an indicator. Excess $K_2Cr_2O_7$ was titrated against 1.05 N $FeSO_4$. To obtain % organic carbon in water samples, the following formula is used and the results were expressed in ppm.

$$\text{OC in ppm} = \frac{\%\ \text{OC} \times 1000}{\frac{100}{1000}}$$

2.6 Headspace equilibration method for dissolved GHG concentration

In addition to surface GHG sampling, pond water samples were collected from a depth of approximately 1 meter to measure

$$\%\ \text{O} = \frac{\{(\text{10-Titration value} \times \text{strength of FeSO}_4 \times 0.003 \times 1.33 \times)\} \times 100}{\text{volume of sample solution}}$$

dissolved GHG concentrations. This phase of sampling was conducted in four fish culture systems (Indian major carp, tilapia, pangasius, and climbing perch) in Fulbaria, Mymensingh, from August to September 2024, at two-week intervals. A total of 120 water samples were collected in 200 mL glass serum bottles, sealed with butyl rubber septa and aluminum crimp caps, and stored in a cool box at 4 °C for analysis within one week. No visible air bubbles were observed in the sample bottle. The samples were degassed by simultaneously injecting high-purity helium and replacing water through the rubber septum of the sealed serum bottle with a hypodermic needle and polyvinyl syringe, with the headspace volume adjusted to 50 mL (Headspace to water ratio was 4 : 1, as optimized by repeated trials with headspace to water ratio of 2 : 1, 3 : 1 and 4 : 1). They were shaken at 300 rpm on a gyratory shaker for 2.30 hour to equilibrate the gases before collecting headspace samples. The gas samples were allowed to rest for 30 minutes following agitation in the gyratory shaker. After reaching equilibrium, a headspace gas sample was collected in a 12 mL evacuated vial with an additional 3 mL of gas injected using a PVC syringe. The processes of sample degassing, shaking, and headspace gas extraction were performed at 25 °C. The dissolved GHGs (N_2O, CO_2, and CH_4) were then quantified using gas chromatography equipped with an electron capture detector (ECD), a thermal conductivity detector (TCD), and a flame ionization detector (FID), with helium as the carrier gas. The gas samples were prepared as per established protocols described by Jahangir *et al.* (2012).[27]

2.7 Estimation of dissolved GHG concentration

The concentrations of N_2O, CO_2, and CH_4 in the water samples were determined by applying Henry's law constants, measured headspace gas concentrations, bottle volume, and the absolute temperature at the time of sample collection. The partial pressures of N_2O, CO_2, and CH_4 in both the equilibrated headspace and water phase were calculated using gas solubility values. Specifically, solubility data were sourced from Weiss (1974) for CO_2,[28] Weiss and Price (1984) for N_2O,[29] and Wilhelm *et al.* (1977) for CH_4,[30] with adjustments made based on the absolute temperature recorded at a depth of 1 meter in the pond.

2.8 Statistical analysis

Surface-level GHGs (CH_4, CO_2, N_2O) emissions were quantified and analyzed utilizing Microsoft Excel. GHG concentrations were analyzed using multiple linear regression to investigate the relationship between various water quality parameters (*e.g.*, pH, dissolved oxygen, temperature, electrical conductivity, total organic carbon, ammonium and nitrate). The regression model was employed to assess the combined and individual effects of these independent variables on the dependent variables, enabling the identification of significant predictors of GHG concentrations. Statistical analyses were conducted including Principal Component Analysis (PCA) using SPSS 27 and Microsoft Excel. PCA identifies patterns in data by explaining the total variance through fewer components, each with eigenvalues representing their contribution to the variance. Components with eigenvalues >1 are considered significant and retained for further analysis. In this study, PCA was used to analyze hydro-parameters and GHG concentrations, revealing significant groupings and relationships among the variables while simplifying the dataset for interpretation.

3 Results

3.1 Water quality of freshwater aquaculture systems with different fish species

Mean pH of the ponds occupied by the different fish species was slightly alkaline (>7.0). The pH was highest in ponds with climbing perch (*ca.* 8.0 ± 0.91) and Indian major carps (*ca.* 7.9 ± 0.5), followed by tilapia ponds (*ca.* 7.6 ± 0.77), while the lowest pH was observed in pangasius ponds (*ca.* 7.1 ± 0.25), which was significantly different ($p < 0.05$) from the other species (Fig. 3a). The dissolved oxygen (DO) concentrations varied significantly across the ponds occupied by different fish species. Ponds with climbing perch exhibited the highest mean DO concentration (*ca.* 6.6 ± 2.54 mg L^{-1}), followed by Indian major carp ponds (*ca.* 5.5 ± 2.4 mg L^{-1}) and tilapia ponds (*ca.* 4.9 ± 2.04 mg L^{-1}). The lowest DO concentration was observed in pangasius ponds (*ca.* 3.2 ± 1.95 mg L^{-1}), which was significantly lower ($p < 0.05$) than DO levels in climbing perch, Indian major carp, and tilapia ponds (Fig. 3b). The highest electrical conductivity (EC) was recorded in pangasius ponds (*ca.* 595.6 ± 245.8 μS cm^{-1}), which was significantly higher ($p < 0.05$) than the EC levels in ponds with Indian major carp (*ca.* 214.5 ± 117.2 μS cm^{-1}), climbing perch (*ca.* 223.2 ± 109.6 μS cm^{-1}), and Tilapia (*ca.* 269.2 ± 108.6 μS cm^{-1}) illustrated in Fig. 3c. The mean water temperature across all ponds was consistent at approximately 32 °C, with no significant variation among ponds occupied by Indian major carp, pangasius, tilapia, or climbing perch illustrated in Fig. 3d.

Ammonium concentrations also exhibited significant differences among the ponds. Pangasius ponds had the highest ammonium concentration (*ca.* 2.22 ± 0.77 mg N L^{-1}), which was markedly higher ($p < 0.05$) than those in climbing perch ponds (*ca.* 0.65 ± 0.30 mg N L^{-1}), Indian major carp ponds (*ca.* 0.60 ± 0.41 mg N L^{-1}), and tilapia ponds (*ca.* 0.50 ± 0.37 mg N L^{-1}) in Fig. 3e. In contrast to ammonium, nitrate concentrations were relatively uniform among the species, with minor variations. The highest nitrate concentration was recorded in tilapia ponds (*ca.* 0.62 ± 0.43 mg N L^{-1}), followed by pangasius ponds (*ca.* 0.69 ± 0.48 mg N L^{-1}), Indian major carp ponds (*ca.* 0.58 ± 0.62 mg N L^{-1}), and climbing perch ponds (*ca.* 0.50 ± 0.45 mg N L^{-1}) in Fig. 3f. Total organic carbon (TOC) levels were highest in tilapia ponds (*ca.* 2070 mg L^{-1}), followed closely by climbing perch ponds (*ca.* 2017 mg L^{-1}) and pangasius ponds (*ca.* 1870 mg L^{-1}), with the lowest TOC concentrations observed in Indian major carp ponds (*ca.* 1653 mg L^{-1}) in Fig. 3g.

3.2 Correlation matrix among GHG concentrations and physicochemical parameters in freshwater ecosystems

The correlation coefficients for all the studied parameters along with their significance levels were presented in Table 2. The correlation analysis revealed key relationships among water quality parameters and GHGs. pH showed a moderate positive

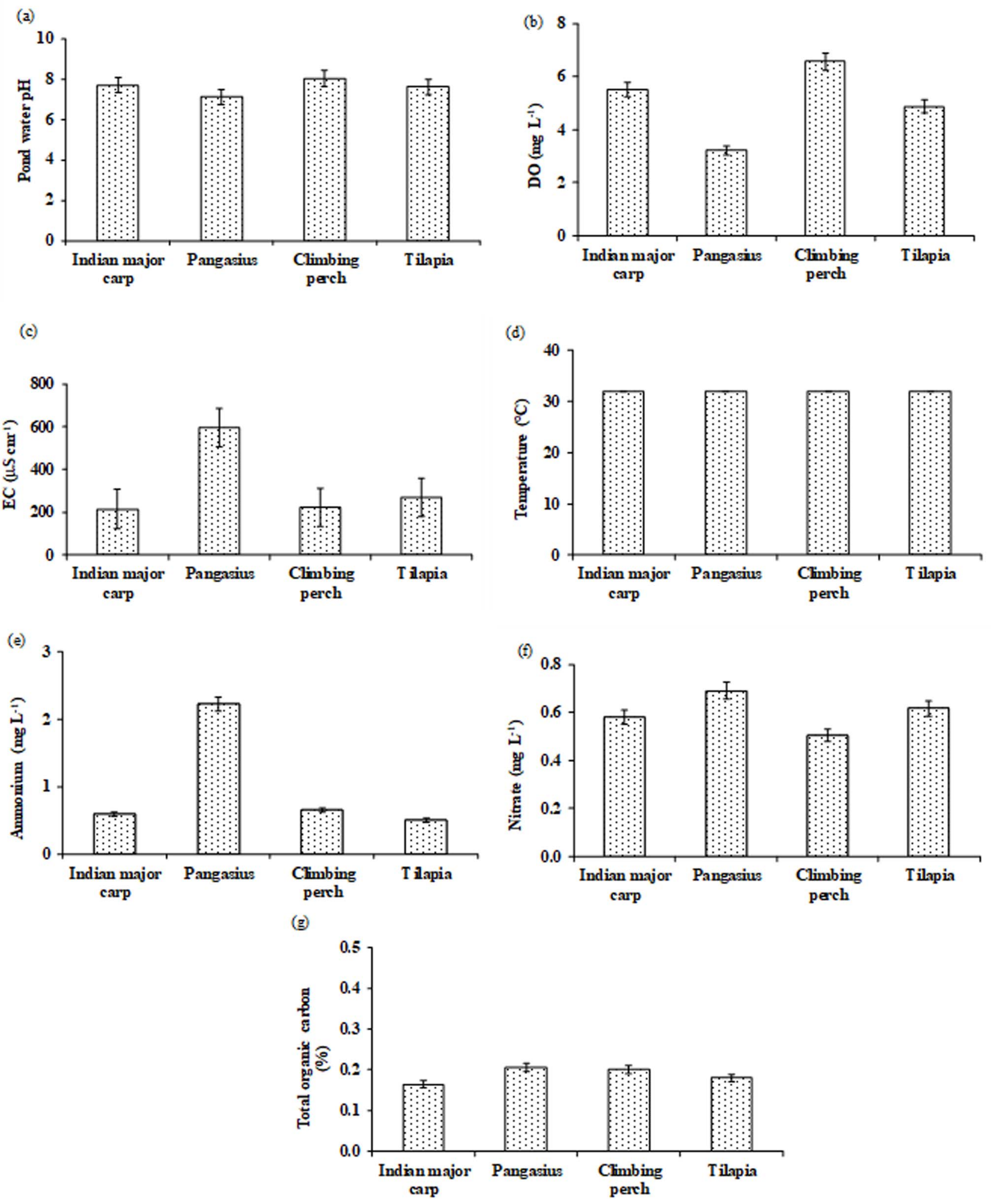

Fig. 3 Variability in physicochemical ((a) pH, (b) DO, (c) EC, (d) temperature) and nutrient ((e) ammonium, (f) nitrate, (g) TOC) parameters of pond water with different fish species and feed loads.

correlation with DO (r = 0.37 and $p < 0.01$) and negative correlations with EC ($r = -0.29$ and $p < 0.01$) and NH_4^+ ($r = -0.34$ and $p < 0.01$). DO is strongly positively correlated with temperature ($r = 0.66$ and $p < 0.01$) but negatively with NH_4^+ ($r = -0.34$ and $p < 0.01$). EC had a strong positive correlation with NH_4^+ ($r = 0.73$ and $p < 0.01$), indicating higher ion concentration with increased NH_4^+. Temperature is weakly negatively correlated with CH_4 ($r = -0.19$ and $p < 0.05$). NH_4^+ also showed a moderate negative correlation with CO_2 ($r = -0.24$ and $p < 0.01$). Likewise, GHGs (CH_4, CO_2, N_2O) exhibit limited significant correlations with other parameters.

3.3 Principal component analysis

The PCA results (*i.e.*, the rotated factor (varimax) matrix of independent variables with differential factor loadings) are summarized in Table 3. The first four principal components (PCs) explain 70.09% of the total variance and have Eigenvalues >1 (Table 3).

In the loading plot, distinct groupings of variables were visible, reflecting the relationships among the parameters (Fig. 4). The first component was strongly associated with NH_4^+ and EC, while the second component was influenced by DO and temperature. The third and fourth components were defined by NO_3^- and pH as well as contributions from GHGs (CH_4, CO_2, and N_2O).

Table 3 Eigenvalues of principal components and their variance contribution

Principal components	Eigenvalue	% of variance	Cumulative%
pH	2.22	24.74	24.74
DO	1.83	20.39	45.13
EC	1.21	13.46	58.60
Temperature	1.03	11.47	70.08
NH_4^+	0.89	9.92	80.00
NO_3^-	0.77	8.61	88.61
CH_4	0.56	6.28	94.90
CO_2	0.27	3.03	97.93
N_2O	0.18	2.06	100.00

3.4 Total surface GHG emissions from freshwater aquaculture

Surface CH_4 emissions time course exhibited increased emissions with the growth of fishes which corresponded well with the feed requirement and supply (Fig. 5). Average CH_4 emissions for Indian major carp, pangasius and tilapia were 0.26, 7.4 and 0.81 kg ha^{-1} day^{-1}, respectively (Fig. 5). The N_2O emissions showed similar trends to CH_4 emissions with the mean emissions were 3.17, 12.63, and 5.2 g N ha^{-1} day^{-1} illustrated in (Fig. 6). The time course of CO_2 emissions were similar to other two GHGs with higher emissions at later stages. The emissions trends were particularly observed for pangasius fish along with the mean CO_2 emissions were 2.57 kg ha^{-1} day^{-1} compared to Indian major carp (0.87 kg ha^{-1} day^{-1}) and tilapia (0.57 kg ha^{-1} day^{-1}) illustrated in (Fig. 7).

3.5 Total dissolved GHG concentration from freshwater aquaculture

The average GHG concentrations from ponds occupied by different fish species over a two month sampling period with 2 weeks intervals showed notable variations for CH_4, CO_2, and N_2O. CH_4 concentrations were highest in ponds with pangasius (173 μg L^{-1} atm^{-1}), significantly exceeding those from climbing perch (21 μg L^{-1} atm^{-1}), tilapia (18 μg L^{-1} atm^{-1}), and Indian major carp (11 μg L^{-1} atm^{-1}), which exhibited the lowest CH_4 concentrations illustrated in Fig. 8a.

CO_2 emissions followed a similar trend, with pangasius ponds emitting the highest levels (6 mg L^{-1} atm^{-1}), far surpassing emissions from climbing perch (3 mg L^{-1} atm^{-1}), tilapia (2 mg L^{-1} atm^{-1}), and Indian major carp (2 mg L^{-1} atm^{-1}) depicted in Fig. 8b. In contrast, N_2O concentrations showed minimal variation across species, with slightly elevated levels observed in climbing perch ponds (6 μg L^{-1} atm^{-1}) compared to Indian major carp, pangasius, and tilapia ponds, all of which had similar emissions (5 μg L^{-1} atm^{-1}) that is represented in Fig. 8c.

Table 2 Correlation matrix of studied parameters and GHGs

	Correlation coefficient								
Parameters	pH	DO	EC	Temperature	NH_4^+	NO_3^-	CH_4 (ppm)	CO_2 (ppm)	N_2O (ppm)
pH	1								
DO	0.373[b]	1							
EC	−0.291[b]	−0.174	1						
Temperature	0.039	0.663[b]	0.101	1					
NH_4^+	−0.340[b]	−0.336[b]	0.728[b]	0.041	1				
NO_3^-	−0.070	0.175	0.024	0.280[b]	0.034	1			
CH_4 (ppm)	0.047	−0.060	−0.003	−0.185[a]	−0.133	−0.014	1		
CO_2 (ppm)	−0.019	−0.054	−0.094	−0.074	−0.237[b]	−0.041		1	
N_2O (ppm)	0.113	0.067	−0.002	0.005	−0.031	−0.014	−0.060	0.038	1

[a] denotes that correlation is significant at the 0.05 level (two-tailed). [b] denotes that correlation is significant at the 0.01 level (two-tailed).

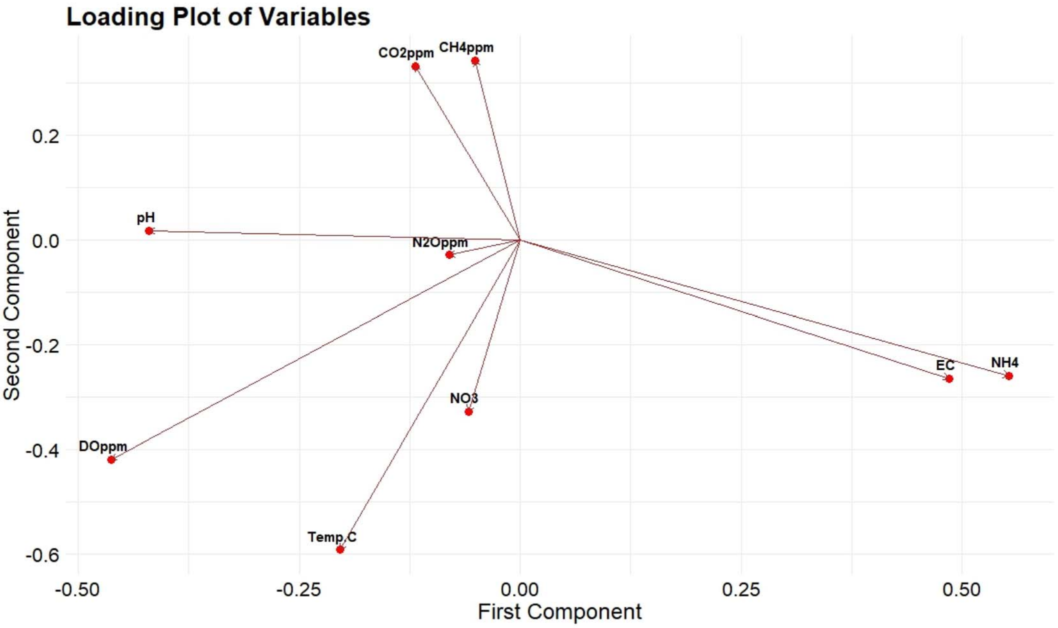

Fig. 4 Loading plot of variables representing principal component analysis (PCA).

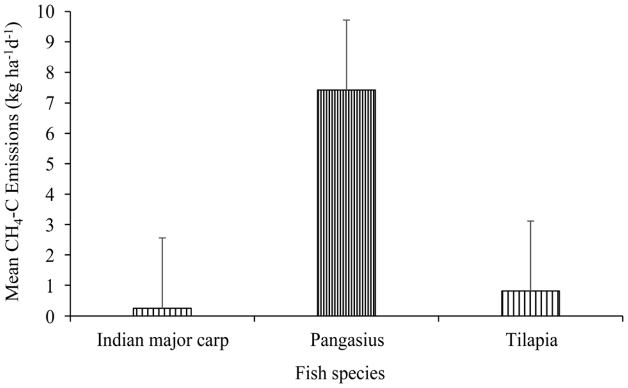

Fig. 5 Methane emissions from three freshwater aquaculture systems ($n = 3$).

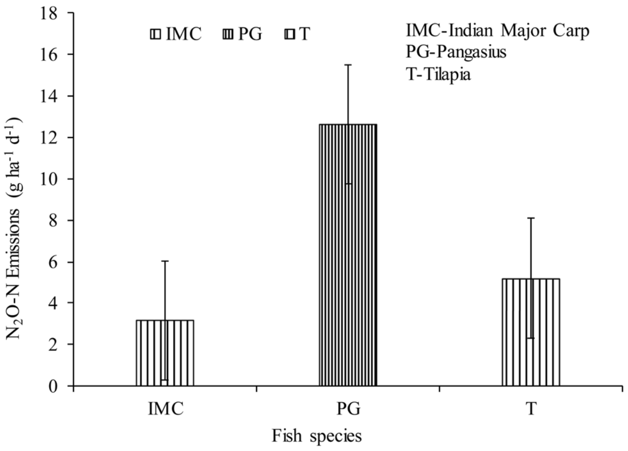

Fig. 6 Nitrous oxide emissions from three freshwater aquaculture systems ($n = 3$).

4. Discussion

This study highlighted the significant role of fish species and feed management in controlling pond water quality and GHG emissions in aquaculture systems. The findings revealed that pangasius catfish (PG) ponds, characterized by semi-intensive feeding practices and the use of sinking feeds, produced the highest emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). These patterns were underpinned by detailed feed input data obtained through semi-structured interviews with farm managers, which quantified consumption rates, protein content, and feed conversion ratios (Table 1) and highlighted the role of sinking *vs.* floating feeds in driving differential organic loading. Specifically, surface CH_4 emissions in PG ponds averaged 7.4 kg ha^{-1} day^{-1}, significantly higher than tilapia (T) (0.81 kg ha^{-1} day^{-1}) and Indian major carp (IMC) (0.26 kg ha^{-1} day^{-1}). Similarly, dissolved CH_4 concentrations were the highest in PG ponds (173 μg L^{-1}), exceeding those of climbing perch (21 μg L^{-1}), T (18 μg L^{-1}), and IMC (11 μg L^{-1}). These results aligned with previous model-based estimations, such as those in Bangladesh, where CH_4 emissions from aquaculture systems averaged 0.89 kg ha^{-1} day^{-1},[31] and highlighted the influence of feed type and organic waste accumulation on methanogenesis.[7,24,32,33] However, CH_4 emissions results from the current study highlight the need for measured data to reduce the uncertainty in GHG emissions from aquaculture systems. In addition, temporal variations in CH_4 emissions, as measured biweekly, suggest more frequent measurement is required for improving the aquaculture GHG estimation. In all three fish species, CH_4 contributes the largest portion of total GHG emissions amounting for 92, 10 and 3.18 tonnes CO_2-e ha^{-1} $year^{-1}$ while the CO_2 and N_2O emissions ranged from 0.2 to 1.0 and from 0.3 to 0.6 tonnes CO_2-e ha^{-1}

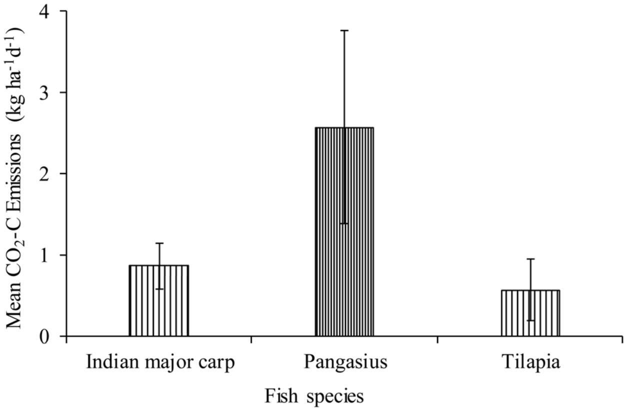

Fig. 7 Carbon dioxide emissions from three freshwater aquaculture systems ($n = 3$).

year^{-1}. However, these data should further be validated with more regional measurements, as comparisons with other studies are very limited due to lack of measured data. The Pangasius aquaculture systems are more conducive to produce CH_4 having lower DO ($\sim$3.0 mg L^{-1}) and sufficient dissolved organic carbon contents ($\sim$0.2 mg L^{-1}). Moreover, aquaculture systems are more favorable for biogenic GHG production and emissions as the soil pH is neutral to alkaline and pond water is rich in nutrient contents *e.g.*, EC in Pangasius system is about 600 μS cm^{-1}. The pond water was also rich in mineral N *e.g.*, NH_4^+ contents were >2.0 mg N L^{-1} and NO_3^- contents were >0.6 mg N L^{-1}. These function as a source of substrate N to produce more N_2O as dissolved organic carbon is also available as a source of electron donor for denitrification to occur. Temperature, even though very favorable in subtropical climate system, is weakly negatively correlated with CH_4 suggesting reduced CH_4 at higher temperatures. NH_4^+ also shows a moderate negative correlation with CO_2 ($r = -0.24$ and $p < 0.01$), likely due to CO_2 uptake in ammonium-rich environments. GHGs (CH_4, CO_2, N_2O) exhibit limited significant correlations with other parameters, implying their concentrations are influenced by factors beyond those analyzed.

Comparatively, surface emissions and dissolved gas concentrations demonstrate notable alignment even though the measurement were carried out in two different seasons (emissions measured in March and April and dissolved gas were measured in August and September), except the N_2O which exhibited higher surface emissions in PG ponds but lower concentrations in dissolved water. This may have been caused by the temporal variations in climatic conditions where the high

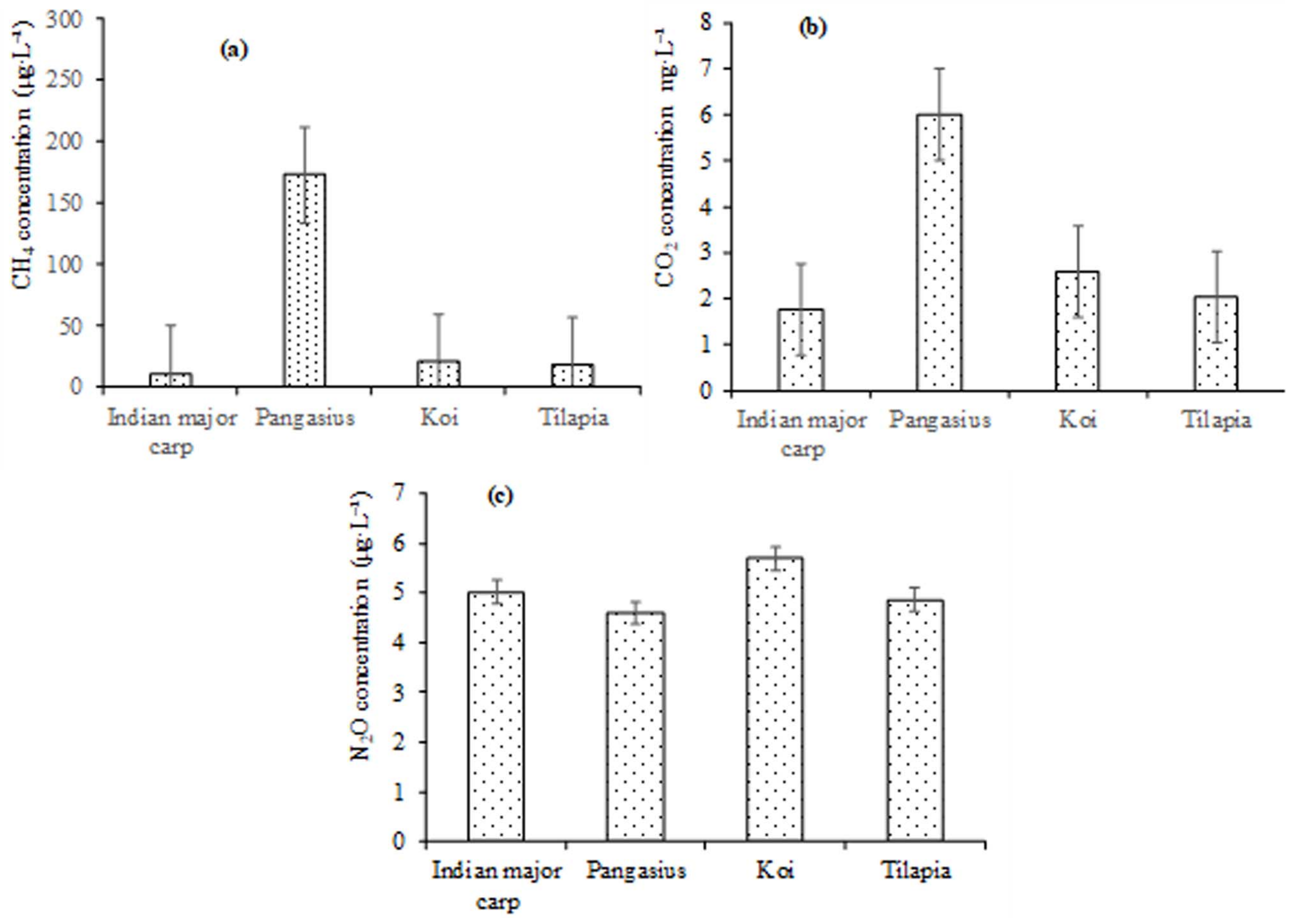

Fig. 8 Dissolved GHGs concentration in pond water by fish species; (a) CH_4, (b) CO_2 and (c) N_2O ($n = 3$).

temperature with corresponding low DO in August and September may have driven denitrification process and reduced the N_2O further to N_2. Surface emissions reflect direct atmospheric fluxes due to increased feed inputs, while dissolved concentrations capture the GHG exchange within the water column over time. For example, dissolved CO_2 concentrations in PG ponds (6 mg C L^{-1} atm^{-1}) were significantly higher than T (2 mg L^{-1} atm^{-1}) and IMC (2 mg L^{-1} atm^{-1}), emphasizing the impact of intensive feeding and organic matter decomposition in PG systems. When compared with other studies, such as one from China reporting CH_4 emissions of 0.79–1.75 kg ha^{-1} day^{-1} for T ponds,[33] and another estimates in Bangladesh with CH_4 emissions averaging 0.89 kg ha^{-1} day^{-1},[31] our study demonstrates higher surface CH_4 emissions (2.83 kg ha^{-1} day^{-1}). These discrepancies highlight the variability in emissions based on species, feed type, and management practices and suggest more measured data are required to improve the emission estimation for national and global aquaculture GHG budgets. Better GHG estimation in aquaculture can also guide to improved management strategies to develop policies for climate impact research and to mitigate climate change effects. The reliance on interview-based feed quantification underscores the value of integrating farm-level management data into GHG assessments, particularly in data-scarce regions like Bangladesh. Future research should focus on alternative feed compositions, the environmental impact of diverse aquaculture systems, and the economic feasibility of sustainable practices to address the growing challenge of aquaculture-related GHG emissions comprehensively.[34–36]

5 Conclusions

The dual analysis of surface and dissolved GHGs is a novel approach, offering a comprehensive understanding of emissions dynamics in aquaculture systems. Our findings capture critical periods of peak fish feeding, directly linked to GHG emissions, providing highly representative data and provided species-specific insights into feed management and environmental impacts, which are essential for developing sustainable aquaculture practices. Pangasius catfish culture systems, among the species studied, exhibited the highest levels of GHG emissions, primarily due to the substantial amount of feed used. This study underscores the importance of optimizing feed ingredients and management practices in aquaculture to mitigate environmental impacts. Sustainable aquaculture growth requires balancing meeting global demand for fish with minimizing environmental footprints, particularly GHG emissions. Adopting environmentally friendly practices, such as selecting species with lower GHG emissions potential and using feeds that are efficiently digested, can significantly reduce the carbon footprint of aquaculture. This research contributes to understanding aquaculture's environmental impact and guides future strategies for sustainable aquaculture development. The findings postulate the need for sustainable aquaculture practices, including optimizing feed types, implementing effective waste management, and monitoring water quality. Policy frameworks should incentivize eco-friendly feeds and enforce regulations to mitigate GHG emissions.

Author contributions

M. M. R. Jahangir: Supervision, fund acquisition, conceptualization, validation; K. R. Luba: filed and lab work, methodology, data curation, analysis, article writing; H. Rashid: Supervision, conceptualization and article editing; M. Akter: methodology, analysis; M. S. Islam: Supervision; R. Khatun: Supervision; M. Zaman: Supervision.

Conflicts of interest

There is no conflicts to declare.

Data availability

Data will be available to share upon request to the corresponding author

References

1 C. Raul, S. S. Pattanaik, S. Prakash, S. K. Vidya and S. Bharti, GHGs emission from aquaculture systems, *J. World Aquac. Soc.*, 2020, 57–61.
2 P. V. V. Prasad, J. M. G. Thomas and S. Narayanan, Global warming effects, *Encycl. Appl. Plant Sci.*, 2017, **3**, 289–299.
3 C. P. Tsai, C. M. Huang, C. S. Yuan, *et al.*, Seasonal and diurnal variations of greenhouse gas emissions from a saline mangrove constructed wetland by using an in situ continuous GHG monitoring system, *Environ. Sci. Pollut. Res.*, 2020, **27**, 15824–15834.
4 L. Ababouch, J. Alder, A. Anganuzzi, U. Barg, D. Bartley (retired), M. Bernal, G. Bianchi, M. Boccia, M. Camilleri, V. Chomo, T. Farmer, N. Franz, C. Fuentevilla, S. Funge-Smith, L. Garibaldi, J. Gee, M. Hasan, R. Hilborn, N. Hishamunda, G. Laurenti, A. Lem, A. Lovatelli, P. Mannini, R. Metzner, J. Sanders, D. Soto, A. Stankus, P. Suuronen, M. Torrie, J. Turner, S. Vannuccini, Y. Ye and X. Zhou, Food and Agriculture Organization of the United Nations, The state of world fisheries and aquaculture 2016: *contributing to food security and nutrition* for all, fisheries and aquaculture department, Food and Agriculture Organization of the United Nations, Rome, 2016.
5 M. Islam, G. Kundu and M. I. Khan, Aquaculture: A Faster Growing Greenhouse Gas Emission Sector in Bangladesh, *Int. J. Ecol. Dev.*, 2020, **35**(3), 44–57.
6 D. Li and J. Liu, Water quality detection for lakes, in. *Water quality monitoring and management*, ed. D. Li and S. Liu, Academic Press, Cambridge, 2019, pp. 221–231.
7 M. J. MacLeod, M. R. Hasan, D. H. F. Robb, *et al.*, Quantifying greenhouse gas emissions from global aquaculture, *Sci. Rep.*, 2020, **10**, 11679.
8 L. Ababouch, S. Vannuccini, *et al.*, *Food and Agriculture Organization of the United Nations, The state of world fisheries and aquaculture 2022: contributing to food security*

and nutrition for all, fisheries and aquaculture department, Food and Agriculture Organization of the United Nations, Rome, 2022, DOI: 10.4060/cc0461en.

9 M. Hossain, Q. S. Afroz, *et al.*, *Fisheries Resources Survey System, Fisheries statistical yearbook of Bangladesh, 2017-18*, Department of Fisheries, Ministry of Fisheries and Livestock, Government of Bangladesh, 2018, vol. 35, p. 129.

10 H. A. Chowdhury, K. M. Haque, *et al.*, *Fisheries Resources Survey System, Fisheries statistical yearbook of Bangladesh, 2019-20 pub*, Department of Fisheries, Ministry of Fisheries and Livestock, Government of Bangladesh, 2021, vol. 37, pp. 141.

11 Fisheries Resources Survey System, *Fisheries statistical yearbook of Bangladesh, 2020-21*, Department of Fisheries, Ministry of Fisheries and Livestock, Government of Bangladesh, 2022, 38, pp. 138.

12 R. Ahmed and M. A. Wahab, Aquaculture in Bangladesh: Growth and impact on food security, *Aquac. Res.*, 2018, **49**(10), 3165–3176.

13 A. L. Gorsky, G. A. Racanelli, A. C. Belvin and R. M. Chambers, Greenhouse gas flux from stormwater ponds in southeastern Virginia (USA), *Anthropocene*, 2019, **28**, 100218.

14 S. K. Malyan, O. Singh, A. Kumar, G. Anand, R. Singh, S. Singh, Z. Yu, J. Kumar, R. K. Fagodiya and A. Kumar, Greenhouse gases trade-off from ponds: an overview of emission process and their driving factors, *Water*, 2022, **14**, 970.

15 Z. Hu, J. W. Lee, K. Chandran, S. Kim and S. K. Khanal, Nitrous oxide (N_2O) emission from aquaculture: a review, *Environ. Sci. Technol.*, 2012, **46**(12), 6470–6480.

16 A. Grinham, S. Albert, N. Deering, M. Dunbabin, D. Bastviken, B. Sherman, C. Lovelock and C. Evans, The importance of small artificial water bodies as sources of methane emissions in Queensland, Australia, *Hydrol. Earth Syst. Sci.*, 2018, **22**, 5281–5298.

17 A. Kumar, T. Yang and M. P. Sharma, Greenhouse gas measurement from Chinese freshwater bodies: A review, *J. Clean. Prod.*, 2019, **233**, 368–378.

18 A. A. P. Baron, L. T. Dyck, H. Amjad, J. Bragg, E. Kroft, J. Newson, K. Oleson, N. J. Casson, R. L. North, J. J. Venkiteswaran and C. J. Whitfield, Differences in ebullitive methane release from small, shallow ponds present challenges for scaling, *Sci. Total Environ.*, 2022, **802**, 149685.

19 B. P. Selvam, S. Natchimuthu, L. Arunachalam and D. Bastviken, Methane and carbon dioxide emissions from inland waters in India–implications for large scale greenhouse gas balances, *Glob. Change Biol.*, 2014, **20**(11), 3397–3407.

20 D. Bastviken, J. Cole, M. Pace and L. Tranvik, Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate, *Global Biogeochem. Cycles*, 2004, **18**, 1–12.

21 S. Hu, Z. Niu, Y. Chen, L. Li and H. Zhang, Global wetlands: potential distribution, wetland loss, and status, *Sci. Total Environ.*, 2017, **586**, 319–327.

22 C. Tong, J. F. Huang, Z. Q. Hu, *et al.*, Diurnal variations of carbon dioxide, methane, and nitrous oxide vertical fluxes in a subtropical estuarine marsh on neap and spring tide days, *Estuaries Coasts*, 2013, **36**, 633–642.

23 H. Tian, C. Lu, G. Chen, B. Tao, S. Pan, S. J. Del Grosso, X. Xu, L. Bruhwiler, S. C. Wofsy, E. A. Kort and S. A. Prior, Contemporary and projected biogenic fluxes of methane and nitrous oxide in North American terrestrial ecosystems, *Front. Ecol. Environ.*, 2012, **10**(10), 528–536.

24 D. H. F. Robb, M. MacLeod, M. R. Hasan and D. Soto, Greenhouse gas emissions from aquaculture: a life cycle assessment of three Asian systems, *FAO Fish. Aquac. Tech. Pap.*, 2017, **609**, 1–9.

25 A. R. Mosier, A. D. Halvorson, C. A. Reule and X. J. Liu, Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado, *J. Environ. Qual.*, 2006, **35**, 1584–1598.

26 A. J. Walkley and I. A. Black, Estimation of soil organic carbon by the chromic acid titration method, *J. Soil Sci.*, 1934, **37**, 29–38.

27 M. M. R. Jahangir, P. Johnston, M. I. Khalil, J. Grant, C. Somers and K. G. Richards, Evaluation of headspace equilibration methods for quantifying greenhouse gases in groundwater, *J. Environ. Manage.*, 2012, **111**, 208–212.

28 R. F. Weiss, Carbon dioxide in water and seawater: the solubility of a non-ideal gas, *Mar. Chem.*, 1974, **2**, 203–215.

29 R. F. Weiss and B. A. Price, Nitrous oxide solubility in water and seawater, *Mar. Chem.*, 1984, **8**, 347–359.

30 E. Wilhelm, R. Battino and R. Wilcock, Low pressure solubility of gases in liquid Water, *Chem. Rev.*, 1977, **77**, 219–261.

31 M. Sarker, M. N. Uddin and B. K. Barman, Methane and nitrous oxide emissions from freshwater aquaculture in Bangladesh: implications for climate change mitigation, *Environ. Sci. Pollut. Res.*, 2021, **28**(9), 11188–11200.

32 S. Mitra, M. A. Khan, R. Nielsen and N. Islam, Total factor productivity and technical efficiency differences of aquaculture farmers in Bangladesh: Do environmental characteristics matter?, *J. World Aquac. Soc.*, 2020, **51**, 1–13.

33 L. Wang, J. Zhang, Q. Zhang and K. Wang, Greenhouse gas emissions from a tilapia pond in subtropical China, *Aquaculture*, 2017, **473**, 76–82.

34 K. S. Prasad, A. Sumalatha, J. V. K. S. C. Rao and V. V. V. Prasad, An Integrated Wireless Aquaculture Monitoring and Feed Management System, *7th International conference on computing methodologies and communication*, 2023.

35 K. M. Green, A. K. Spalding, M. Ward, A. Levine, E. A. Wolters, S. L. Hamilton and L. Rice, Oregon shellfish farmers: Perceptions of stressors, adaptive strategies, and policy linkages, *Ocean Coast. Manag.*, 2023, **234**, 106475.

36 A. Wilfart, F. Garcia-Launay, F. Terrier, E. Soudé, P. Aguirre and S. Skiba-Cassy, A step towards sustainable aquaculture: Multiobjective feed formulation reduces environmental impacts at feed and farm levels for rainbow trout, *Aquaculture*, 2023, **562**, 738826.