Quantification of benthic–pelagic nutrient coupling and air–water gas exchange in anthropogenically impacted freshwater ecosystems

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Abstract

Freshwater systems are vital in the control of biogeochemical cycles, biodiversity, and deliver valuable ecosystem services. Some of the most significant processes, which support these ecosystems, include benthic-pelagic nutrient interactions and air-water gaseous exchange. The processes are important in the nutrient availability, primary productivity, and greenhouse gases. The research will measure the effects of anthropogenic processes, such as agricultural runoff and industrial pollution, in a tropical freshwater ecosystem on these coupled processes. Field sampling, laboratory, and statistical methods are used to estimate the seasonal nutrient fluxes, gaseous exchange rates, and the association between anthropogenic stress and ecosystem functioning. The findings indicate that there are considerable seasonal differences in physicochemical characteristics, nutrient levels, and gaseous exchange. In particular, the nutrient fluxes were the most intense during the monsoon season: nitrogen flux 43.9 mg m^2/day and phosphorus flux 15.9 mg m^2/day. The CO_2 flux was higher in the monsoon of 272.6 mg m^2/day compared to the winter of 118.5 mg m^2/day, and the methane flux varied

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between 8.1 and 22.8 mg m ^{2}/day. Statistical results indicated that there were strong relationships among biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrient fluxes that supported the effects of nutrient loading by human activities on the microbial activity and greenhouse gas emissions. The study finds that the anthropogenic effects are greatly contributing to the cycling of nutrients, greenhouse gases, and the stress of the ecosystem, especially when there is a high level of nutrient loading. The research should be extended to long-term monitoring and sensor integration in real-time to enhance ecosystem management and sustainability in the future.

Keywords: Benthic-pelagic coupling, Nutrient flux, Air-water gas exchange, Anthropogenic impact, Greenhouse gas emissions, Eutrophication, Freshwater ecosystems

Introduction

Freshwater systems (lakes, rivers, and wetlands) are important in ensuring the ecological balance by sustaining biodiversity, biogeochemical cycles, and essential ecosystem services like the supply of water, nutrient recycling, and control of climate (Klump, Fitzgerald and Waplesa, 2009).

It is the dynamic interfaces in which physical, chemical, and biological processes interact and are in continuous interaction with one another that determine the overall productivity and stability of the ecosystem. The exchange of nutrients between the bottom sediments (benthic zone) and the water column (pelagic zone) is one of these processes and is referred to as the benthic-pelagic coupling (Lopes, 2024; Foster and Fulweiler, 2014; Ferguson and Eyre, 2010). The interaction is highly influential in nutrient availability, primary productivity, and internal loading, especially in nutrient-enhanced or disturbed environments. At the same time, another important process that controls the movement of gases (carbon dioxide (CO_2), methane (CH_4), and oxygen (O_2)) between the water bodies and the atmosphere is air-water gas exchange (Bates and Mathis, 2009; Steffens, Henriksson and Santos, 2026). Such gas fluxes are crucial to comprehending the metabolism of the ecosystem, gas dynamics, and the contribution of freshwater bodies as sources or sinks of greenhouse gases (Moraes *et al.,* 2023). The relationship between nutrient dynamics and gaseous exchange processes is usually an indication of biological activity and environmental stressful situations (Porter and Cornwell, 2024). Nevertheless, freshwater ecosystems are becoming more vulnerable to human activities such as industrial effluents, agricultural effluents, and urbanization, which are seriously distorting the natural operation of the ecosystem (Jickells *et al.*, 2017). An overload of nutrients will usually result in eutrophication, hypoxia, and increased greenhouse gas emissions, thus affecting both the benthic-pelagic interactions and the air-water exchange mechanisms (Biçe *et al.*, 2025). Although more and more research is going into this area, a considerable gap in the quantitative knowledge of how these coupled processes react to different levels of human influence still persists, especially in tropical and developing areas. Thus, the current study will set out to measure benthic-pelagic nutrient coupling and air- water gas exchange in anthropogenically affected freshwater systems, and the role of enriching nutrients and polluting the system in these interrelated processes (Mangan *et al.*, 2022; Ehrnsten *et al.*, 2020; Cavalli *et al.*, 2025).

- The study presents a quantitative evaluation of benthic-pelagic nutrient coupling by estimating the nutrient fluxes between the sediment and the water at different degrees of anthropogenic impact, giving a better understanding of the internal nutrient loading processes of freshwater ecosystems.
- It assesses the air-water gas exchange processes by approximating the CO_2, CH_4, and O_2 fluxes and determining the connection between nutrient enrichment, ecosystem metabolism, and greenhouse gas emissions.
- The study is an interface between nutrient dynamics and gas exchange analysis to demonstrate the impact of anthropogenic stressors on ecosystem functioning, to offer a complete framework to more effectively monitor and manage freshwater systems.

The structure of the paper will be as follows: Section I will give the importance of the freshwater ecosystem and benthic-pelagic coupling and air-water gas exchange in the functions of the ecosystem. Section II gives the literature review about the important processes of nutrient cycling and gas exchange in the aquatic system. Section III explains the materials and methods, which include the area of study, the sampling design, and the way of measuring nutrient flux and gas exchange. The results, which include seasonal variations in physicochemical properties, nutrient content, and gas exchanges, and statistical analysis, are presented in section IV. Section V deals with the findings and compares them with the other previous works, and the impacts of anthropogenic activities on the processes of the ecosystems. Section VI summarizes the research and provides ideas on the influence of human activities on freshwater ecosystems and suggestions for future research.

Literature Review

Benthic-pelagic interaction is an important process in controlling the nutrient cycling and metabolism of aquatic ecosystems, as well as the air-water exchange of gases. These interactions control the movement of nutrients and gases among sediments, the water column, and the atmosphere, thus affecting general ecosystem functioning at natural and anthropogenic environments. Coastal and estuarine ecosystems have been of high interest in terms of the air-water exchange of CO_2, which has been highly vulnerable to climatic variability and the productivity of the ecosystems. Abnormal warming states had a great impact on CO_2 fluxes and net ecosystem production in lagoons at the coast, highlighting the importance of temperature and biological activity in regulating the processes of gas exchange (Ávila-López *et al.*, 2017). Aquatic metabolism and reaeration, measured by oxygen dynamics, are a powerful paradigm to connect gas exchange with ecosystem productivity (Holtgrieve *et al.,* 2010).

Benthic-pelagic interaction is the key to controlling nutrient levels via sediment-water interactions. Benthic nutrient regeneration and coupling strength in estuarine systems are greatly affected by climate change (Fulweiler and Nixon, 2009). Such interactions play a crucial role in stabilizing the ecosystems and in biogeochemical turnover, especially when subjected to altered environmental conditions (Liu *et al.*, 2026). Enrichment of nutrients, particularly nitrogen, has been cited as a major factor in changing the ecosystem. Nitrogen loading increases affect benthic communities and the nutrient cycle in sediments, promoting internal nutrient cycling (Griffiths *et al.*, 2017). Sediment nutrient fluxes in anthropogenically-influenced environments are usually a secondary source of nutrients. External inputs of pollution and organic matter build-up are linked to significant benthic nutrient release of mangrove sediments in disturbed estuaries (Kaiser *et al.*, 2015).

The anthropogenic processes that exacerbate the nutrient loading and change the natural biogeochemical processes include urbanization, agricultural runoff, and industrial discharge. The results of these changes usually are eutrophication, hypoxia, and increasing greenhouse gases, which enhance the interaction between the nutrient cycle and gas exchange mechanisms. Although the integrated quantification of benthic and pelagic nutrient fluxes and air-water gas exchange in freshwater systems under different levels of human influence has been studied, there is still an insufficient amount of knowledge regarding the marine and estuarine systems. Thus, the proposed research seeks to fill this knowledge gap by offering an in-depth quantification of the processes of nutrient coupling and gas exchange in the anthropogenically impacted freshwater ecosystems, to a more profound understanding of the ecological and biogeochemical response.

Materials and Methods

This paper employs an interdisciplinary approach that involves field sampling, laboratory analysis, nutrient flux estimation, gas exchange measurements, and statistical analysis to assess benthic-pelagic coupling and anthropogenic effects within a freshwater ecosystem, as displayed in figure 1.

Figure 1 shows the general methodological scheme followed in this work, which describes how the field sampling will be performed and how the data analysis will be organized in a sequence. It describes some of the important steps, such as the selection of the study area and seasonal sampling, water and sediment samples, laboratory analysis of the physicochemical and nutrient parameters, determination of benthic-pelagic nutrient flux by incubating sediment cores, and determination of air-water gas exchange using the floating chamber method. Anthropogenic impact assessment in the framework is achieved by land-use and pollution indicators, and then statistically analyzed by correlation and regression ($p < 0.05$) in R and SPSS. The combination of these methods allows for the analysis of the dynamics of nutrients, gas flux, and the interconnection with the anthropogenic stress of the environment.

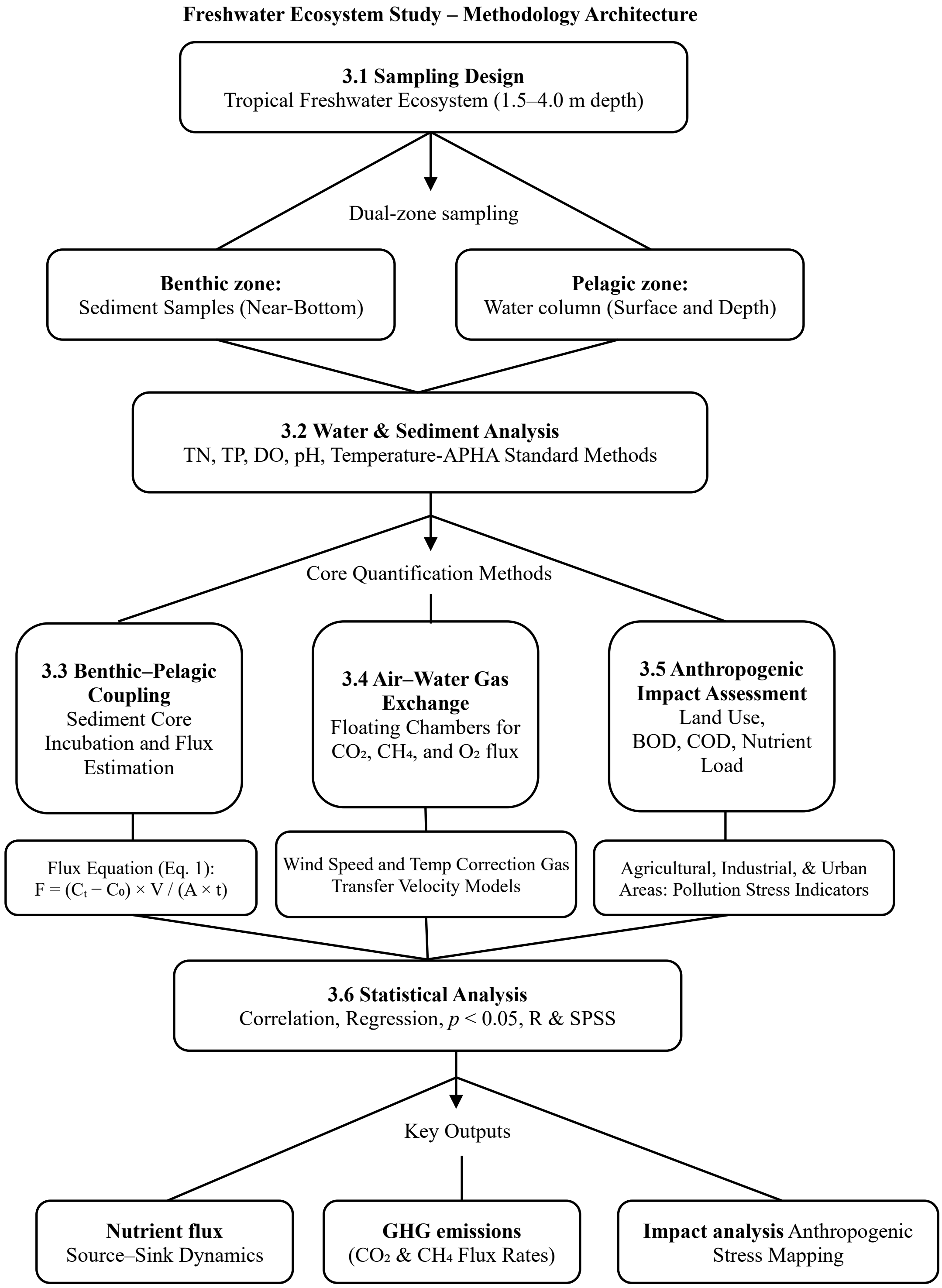

Figure 1: Methodology for nutrient coupling and gas exchange assessment.

Sampling Design

The experiment was carried out in a shallow freshwater habitat with clear-cut benthic and pelagic habitats, with a mean depth of 1.5-4.0 m. It has a tropical climate with seasonal changes, with temperature differences of 22°C to 32°C and precipitation that is mostly received during the monsoon season, affecting the hydrological and nutrient processes. Anthropogenic processes also have a significant influence on the area of study, including agricultural run-off, domestic sewage discharge, and localized input of industries, leading to a high level of nutrient loading and organic pollution. These aspects cause the eutrophic conditions and influence the benthic-pelagic nutrient exchange processes, the air-water gas flux. The sampling points were selected strategically, in various places of impact, in such a way that spatial variations in the system are captured. The sampling was done at the representative sites of both the benthic (sediment) and the pelagic (water column) areas of the chosen freshwater ecosystem. Several stations were set up to indicate spatially varied characteristics as a result of anthropogenic activities. The samples were not taken less frequently, monthly, to take into account seasonal changes. Measurements were done at various depths at the surface, depth, and near-bottom layers at each station to assess vertical gradients in physicochemical properties and nutrient dynamics.

Water and Sediment Analysis

The major physicochemical and nutrient parameters were examined in water and sediment samples. Nutrient levels were measured as nutrient concentrations, e.g., total nitrogen (TN) and total phosphorus (TP), to measure the enrichment of the nutrient. Moreover, the in-situ measurements of the dissolved oxygen (DO), pH, and temperature were made with calibrated probes. Laboratory tests were conducted as recommended by the American Public Health Association, following standard procedures to ensure accuracy and comparability of the results.

Quantification of Benthic–Pelagic Coupling

The Benthic pelagic nutrient coupling was determined by estimating the sediment-water nutrient fluxes. Intact sediment core incubation experiments were done under controlled conditions to determine the release or uptake of nutrients at the sediment-water interface. The flux (F) of nutrients was obtained with the help of the following equation:

$$F = \frac{(C_t - C_0) \times V}{A \times t} \tag{1}$$

In equation (1), where:

F = nutrient flux (mg m^{-2} day^{-1})

C_0 and C_t = initial and final nutrient concentrations (mg L^{-1}),

V = volume of overlying water (L),

A = surface area of sediment core (m^2),

t = incubation time (days).

The method allows for establishing whether the sediments are a source or sink of nutrients in different environmental conditions.

Air–Water Gas Exchange Measurement

The air-water gas exchange was also evaluated by estimating the CO_2, CH_4, and O_2 fluxes using the floating chamber technique. The chambers were used on the water surface, and the concentration of gases was observed with time. The gas flux was determined as the rate of change in the concentration of the gas in the chamber. In addition, gas transfer velocity models took into account the environmental factors such as the wind speed and temperature. The calculated fluxes give an understanding of the contribution of the freshwater systems to the greenhouse gas emissions and the oxygen reactions.

Anthropogenic Impact Assessment

Land-use analysis and indicators of water quality were used to measure the anthropogenic factor in the study area. The land-use patterns including the agricultural, industrial, and urban ones were evaluated in order to identified the potential sources of nutrient loading. The extent of the environmental stress and its impact on the environment process were quantified by assessing pollution measures such as the biochemical oxygen demand (BOD), chemical oxygen demand (COD) and the nutrient levels.

Statistical Analysis

The dynamics of nutrients and gas exchange were tested in terms of correlation. The relationships between the nutrient levels and the gas fluxes were determined by correlation analysis, and regression models were constructed to measure relationships. The p-value ($p < 0.05$) was used as a measure of statistical significance. The standard software packages, such as the R software and SPSS, were used to carry out all the analyses.

Results

Physicochemical Characteristics

Physicochemical characteristics of the freshwater system showed significant seasonal and vertical changes, driven by climatic conditions and anthropogenic contributions. During winter and summer, the surface water temperature was between 22.3°C and 31.9°C, and the bottom water temperature was a bit lower because the sunlight penetration was less. During the seasons, the pH was kept at a fairly high pH (7.2-8.2). It was also noted that dissolved oxygen (DO) decreases with depth, with low levels in the summer (4.3 mg L^{-1} at the surface and 3.7 mg L^{-1} near the bottom), which is related to the increased oxygen requirements of the biology and to stratification processes. The values of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were greater in the monsoon season (6.6 mg L^{-1} and 35.8 mg L^{-1}, respectively), indicating a high contribution of organic matter due to surface runoff. These patterns indicate that seasonal hydrology and external sources of pollution can have a significant impact on the water quality dynamics.

Table 1: Seasonal variation of physicochemical parameters and nutrient concentrations in the freshwater ecosystem.

Season	Temp (°C)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	TN (mg/L)	TP (mg/L)
Winter	22.3	6.8	3.2	18.4	1.10	0.08
Summer	31.9	4.3	5.8	29.6	1.68	0.13
Monsoon	27.8	5.1	6.6	35.8	2.40	0.20
Post-Monsoon	25.4	5.7	4.7	24.9	1.82	0.15

As indicated in table 1, Temperature increased by 22.3°C to 31.9°C (winter to summer, respectively), and dissolved oxygen fell by 6.8 mg/L to 4.3 mg/L, and there was an inverse relation between the two. BOD and COD increased by 3.2 mg/L and 18.4 mg/L in winter to maximum values of 6.6 mg/L and 35.8 mg/L in monsoon, indicating increased organic load. There was also an increase in the levels of the nutrients, including TN, which went up to

2.40mg/L and TP, which went up to 0.20mg/L, then decreased slightly in the post-monsoon period (TN: 1.82mg/L; TP: 0.15mg/L), which shows that are largely seasonal and anthropogenic.

Nutrient Dynamics

Spatially, stations located near anthropogenic discharge points exhibited significantly higher nutrient levels compared to relatively undisturbed zones, confirming the role of human activities in nutrient enrichment.

There were significant spatial and temporal variations in nutrient concentrations, especially total nitrogen (TN) and total phosphorus (TP). The bottom waters and sediments showed a continual increase in concentrations with respect to the surface water, which was an indication of nutrient accumulation and internal loading potential. TN in water rose with the season to a high of 2.40 mg L^{-1} in the monsoon compared to 1.10 mg L^{-1} in winter, whereas TP rose to 0.20 mg L^{-1} during the same season compared to 0.08 mg L^{-1} in winter. The concentrations of the nutrients in sediments showed the same pattern, with the highest concentrations observed during the monsoon period (TN: ~1080 mg kg^{-1}; TP: ~740 mg kg^{-1}). The presence of these high levels in the monsoon implies that there are high levels of external nutrients through agricultural runoff and discharge of wastewater. Geographically, the nutrient content of the relatively stationary areas was much higher in areas where anthropogenic discharge occurred than in relatively pristine areas, which validated the anthropogenic contribution to the enrichment of nutrients.

Benthic–Pelagic Nutrient Flux

The interface between the sediment and water showed active nutrient exchange, with the quantitative fluxes showing that the sediments were mainly a source of nutrients to the water column above it. There were positive values of flux, indicating that nutrient release was taking place in the sediments in all seasons.

Nitrogen flux varied between +18.2 mg m^{-2} day^{-1} in winter and +43.9 mg m^{-2} day^{-1} in the monsoon period, whereas phosphorus flux varied between +6.0 and +15.9 mg m^{-2} day^{-1}. The monsoon periods have the highest fluxes that may be explained by deposition of organic matter, microbial mineralization, and low oxygen levels at the sediment-water interface. These findings reveal that there is a high degree of benthic-pelagic interactions in which internal nutrient loads play a major role in the overall nutrient supply in the water column, especially in eutrophic conditions. Figure 2 shows the seasonal change in the nutrient flux.

Figure 2 displays definite seasonal fluctuation in benthic-pelagic nutrient flux, where the sediments served as a reliable source of nutrients during the year. The increase in nitrogen flux in winter was +18.2 mg m^{-2} day^{-1} and in summer was +33.8 mg m^{-2} day^{-1}, which peaked in the monsoon to +43.9 mg m^{-2} day^{-1} and then went down to +26.8 mg m^{-2} day^{-1} in the post-monsoon. On the same note, phosphorus flux increased to +6.0 mg m^{-2} day^{-1} in winter to +15.9 mg m^{-2} day^{-1} in monsoon and decreased to +9.9 mg m^{-2} day^{-1} in post-monsoon, which implies an increased nutrient release during the monsoon season.

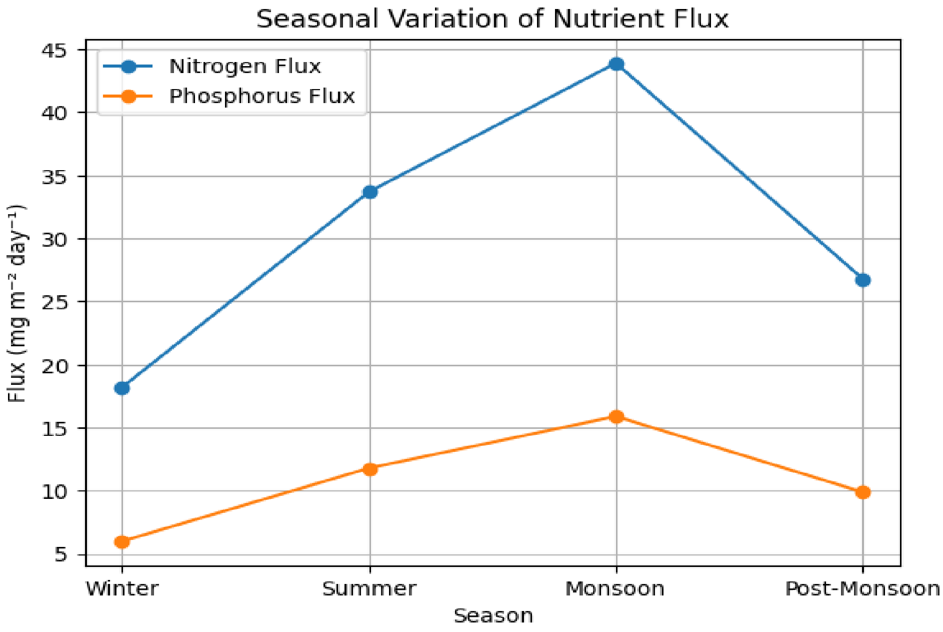

Figure 2: Seasonal variation of benthic–pelagic nitrogen and phosphorus flux at the sediment–water interface.

Air–Water Gas Exchange

Measures of air-water gas exchange showed that the freshwater system was a net source of greenhouse gases, especially carbon dioxide (CO_2) and methane (CH_4), and that oxygen (O_2) flux was net. The CO_2 flux also rose to 272.6 mg m^{-2} day^{-1} during the monsoon as compared to 118.5 mg m^{-2} day^{-1} in winter, with CH_4 flux between 8.1 and 22.8 mg m^{-2} day^{-1}. Conversely, the values of O_2 flux were always negative, with the highest consumption recorded in the monsoon period (−190.6 mg m^{-2} day^{-1}), indicating rapid respiration and decomposition rates.

The seasonal patterns showed that gas emissions were highly correlated with temperature, nutrient availability, and microbial activity, with maximum emissions during high organic loading and low oxygen conditions.

Table 2: Seasonal variation of nutrient fluxes and air–water gas exchange rates in the freshwater ecosystem.

Season	N Flux	P Flux	CO_2 Flux	CH_4 Flux	O_2 Flux
Winter	18.2	6.0	118.5	8.1	-94.2
Summer	33.8	11.8	220.4	16.2	-168.3
Monsoon	43.9	15.9	272.6	22.8	-190.6
Post-Monsoon	26.8	9.9	182.3	13.5	-135.7

Table 2 shows that the nutrient and gas fluxes are highly seasonal. Nitrogen (N) flux went up to 18.2 mg m^{-2} day^{-1} (winter) to peak at 43.9 mg m^{-2} day^{-1}, and phosphorus (P) flux went up to 15.9 mg m^{-2} day^{-1}, suggesting an increase in sediment nutrient release. The same was also observed in the CO_2 and CH_4 fluxes, which were higher during monsoon (272.6 and 22.8 mg m^{-2} day^{-1}), indicating enhanced decomposition and microbial activity. Contrastingly, O_2 flux was always negative in all seasons, with the least value (−190.6 mg m^{-2} day^{-1})

recorded during the monsoon, implying more oxygen consumed and stress on the ecosystem due to large nutrient loading. Figure 3 shows the seasonal change in the gas flux.

Figure 3 indicates that CO_2 and CH_4 fluxes rise in the winter (~120 and 8 mg m^{-2} day^{-1}) to the peak in the monsoon (~270 and 22.8 mg m^{-2} day^{-1}), and O_2 flux is more negative, reaching about -190.6 mg m^{-2} day^{-1}, which indicates an increased microbial activity and lack of oxygen.

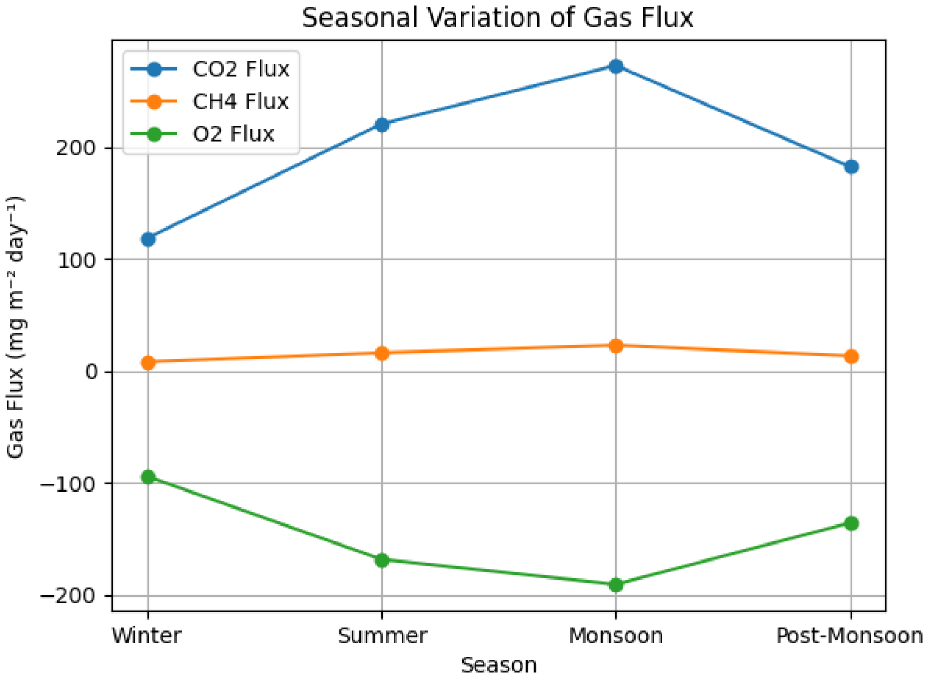

Figure 3: Seasonal variation of air–water gas flux.

Influence of Anthropogenic Activities

Strong statistical relationships between pollution indicators and measured fluxes showed the effect of anthropogenic activities on the processes of nutrient dynamics and gas exchange. Correlation analysis showed that there were significant positive correlations between BOD and nutrient flux ($r = 0.84$), CO_2 flux ($r = 0.88$), and CH_4 flux ($r = 0.81$). In the same vein, COD and nutrient levels were also highly correlated with gas emissions ($r > 0.80$, $p < 0.05$). These results reveal that more organic and nutrient loading due to agricultural runoff, sewage discharge, and other anthropogenic sources results in a greater microbial activity and, therefore, more nutrient release by the sediments and higher emissions of greenhouse gases. In general, the findings indicate that the anthropogenic stress, nutrient enrichment, benthic-pelagic interactions, and the processes of air-water gas exchange are closely interconnected, which shows the importance of human activities in the modification of the freshwater ecosystem functioning.

Discussion

Compare Nutrient Fluxes with Previous Studies

The freshwater findings and the Jinhae Bay study indicate that sediments serve as a main source of nutrients to the water column, but the amounts and the seasonal processes are different. The freshwater analysis indicates that nitrogen (N) flux is maximal during the monsoon at 43.9 mg m^{-2} day^{-1}, as a result of external agricultural runoff and input of organic matter. Conversely, a marine experiment in Jinhae Bay measured the nitrogen flux at 1.50 to 2.07 mmol m^{-2} day^{-1}. in winter. The Jinhae Bay nitrogen flux upon conversion to mass is approximately 21.0 to 29.0 mg m^{-2} day^{-1}, compared to 29.0 day in the freshwater system, but it is similar to that of the winter and post-monsoon seasons. The difference is greater with respect to the phosphorus (P) dynamics. The freshwater system has high phosphorus release between 6.0 and 15.9 mg m^{-2} day^{-1}, and Jinhae Bay has very low phosphate release of 0.02-0.05 mmol m^{-2} day^{-1} (about 0.62-1.55 mg m^{-2} day^{-1}). It shows that the freshwater study site has almost a tenfold amount of internal phosphorus loading in the winter as compared to Jinhae Bay. Although these studies do not identify differences in the scale, both works note a strong benthic-pelagic interaction in terms of sediment nutrient regeneration in the process of primary production and nutrient-sustaining water columns.

Table 3: Comparative analysis of nutrient fluxes and controlling factors between freshwater and marine ecosystems.

Parameter	Observed Values (Freshwater)	Reported Marine Values (Jinhae Bay)
Nitrogen Flux	18.2 – 43.9 mg m^{-2} day^{-1}	~21.0 – 29.0 mg m^{-2} day^{-1}
Phosphorus Flux	6.0 – 15.9 mg m^{-2} day^{-1}	~0.62 – 1.55 mg m^{-2} day^{-1}
Primary Driver	Monsoon Runoff / Sewage	Aquaculture Biodeposits
Peak Season	Monsoon	(Summer Hypoxia - inferred)

As presented in table 3, the freshwater system is more variable and greater in magnitude in nutrient fluxes, with nitrogen and phosphorus varying between 18.2 and 43.9 mg m^{-2} day^{-1}, and 6.0 to 15.9 mg m^{-2} day^{-1}, respectively, compared to the marine system (~21.0 to 29.0 mg m^{-2} day^{-1}). The prevailing forces vary widely, with monsoon runoff and sewage input in the freshwater system, and the aquaculture bio deposits in the marine environment. The maximum nutrient flux is related to the monsoon season in freshwater, and in the marine system to summer hypoxia, with clear environmental and anthropogenic regulation in different ecosystems (An *et al.*, 2025).

The high nutrient levels, where total nitrogen ranged between 1.10 mg/L (winter) and 2.40 mg/L (monsoon), and the total phosphorus ranged between 0.08 and 0.20 mg/L, are indicative of severe eutrophication in the system. This adds to primary productivity and results in greater deposition of organic matter in the sediments. This leads to an increased microbial activity, which speeds up the decomposition process at the sediment-water interface and increases nutrient release.

The stress of an anthropogenic character is clearly observed in the growth of the pollution load, BOD, with the increase of 3.2 to 6.6 mg/L, and COD, with the increase of 18.4 to 35.8 mg/L. This high organic input has a huge impact on the gas emission, whereby CO 2 flux has risen to 272.6 mg m^{-2} day^{-1}, and CH_4 flux has risen to 22.8 mg m^{-2} day^{-1}, especially in the monsoon season. These tendencies confirm the fact that nutrient loading caused by humans increases the respiration and anaerobic activities of microorganisms, which increases greenhouse gas emissions. The ecological consequences are reflected in ongoing negative oxygen flux, decreasing to the value of -94.2 down to -190.6 mg m^{-2} day^{-1} that represents major oxygen depletion and hypoxia. This may have an adverse effect on aquatic life, disturb trophic relationships, and lower the overall health of the ecosystem, particularly during the high temperature and nutrient-promoting seasons.

This study is novel in that it is critically evaluated with both benthic-pelagic nutrient coupling and air-water gas exchange under seasonal and anthropogenic conditions. The connection between nutrient dynamics and the gas fluxes through the measured values will provide a complete picture of how human activity enhances the biogeochemical processes in the freshwater ecosystems.

Conclusion

This experiment presents a combined evaluation of the benthic-pelagic nutrient coupling and air-water gas exchange of an anthropogenically disturbed freshwater ecosystem with a high level of seasonal variation and anthropogenic impact. There were clear tendencies in physicochemical parameters since the temperature increased during winter (22.3°C) and during summer (31.9°C), and dissolved oxygen decreased to 4.3 mg L^{-1}, i.e., the biological activity and oxygen demand are high. Physicochemical parameters exhibited evident trends, where the temperature rose in winter (22.3°C) and in summer (31.9°C), dissolved oxygen reduced to 4.3 mg L^{-1}, meaning that the biological activity and oxygen demand are high. The concentrations of nutrients were much higher under monsoon conditions, where total nitrogen level had gone up by 1.10-2.40 mg L^{-1}, and total phosphorus by 0.080-0.20 mg L^{-1}, indicating eutrophic conditions. Nutrient fluxes of sediments and water were consistently positive, with a range of nitrogen (18.2 to 43.9 mg m^{-2} day^{-1}) and phosphorus (6.0 to 15.9 mg m^{-2} day^{-1}) that supported the claim that sediments are a significant internal nutrient source. The results of gas exchange indicated that the system was a net source of greenhouse gases, with CO_2 flux varying between 118.5 and 272.6 mg m^{-2} day^{-1} and CH_4 between 8.1 and 22.8 mg m^{-2} day^{-1} and O_2 flux negative (-94.2 -190.6 mg m^{-2} day^{-1}). There were strong statistical relationships between the pollution indicators and the ecosystem processes, with BOD positively correlated with nutrient flux (r = 0.84), CO_2 (r = 0.88), and CH_4 (r = 0.81). Altogether, the results indicate that the anthropogenic nutrient loading promotes microbial activity as well as nutrient cycling and greenhouse gas emissions, resulting in ecological stress. The future research in this area should be directed towards the monitoring of the long-term, modeling methods, and the integration of real-time sensors to enhance ecosystem management and sustainability.

Ethical Considerations

Some of the ethical considerations of this study were that there would be transparency in data collection and analysis, the sensitivity of any data involved would be ensured, and that the possible harm to the environment during the field sampling exercise would be minimal. The sampling processes were carried out in line with the set ethical practices and local laws. Moreover, the study complied with the principles of responsible environmental research in that the anthropogenic effects and the environmental implications were thoroughly considered. The purpose of the study is to have precise and objective findings that would lead to the proper management of the ecosystems.

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