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Nutrient cycling in aquatic ecosystems and the role of benthic microorganisms in ecosystem functioning

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Abstract

The paper reviews how benthic microorganisms enhance nutrient cycling in water bodies, yet this process is not yet incorporated into ecosystem models. Recycling of nutrients is vital to biodiversity, productivity, and ecological stability, and microorganisms in sediments bacteria, archaea, and microalgae play a significant role. They mediate critical biogeochemical processes of nitrogen, phosphorus, carbon, and Sulfur, and they connect benthic and pelagic systems. Nevertheless, the majority of current models do not take their quantitative contribution to nutrient regulation seriously. To overcome this, a conceptual model was developed by combining empirical knowledge of nutrient fluxes, microbial community structure, and sediment chemistry. This leads to the microbial metabolic pathways and sediment biogeochemical dynamics in the resulting Benthic Integrated Nutrient Cycling Model (BINCM). Simulated experiments relied on changes in dissolved oxygen and organic matter to describe biologically the patterns of nutrient flux. Findings show that benthic microbes are essential for nutrient cycling through denitrification, nitrification, sulfate reduction, and phosphorus mobilization. The microbial activity under controlled conditions demonstrated that the model simulations indicated nutrient fluxes could change by 30-45% according to the model. High carbon of organic substances and moderate oxygen concentration favored greater microbial diversity and a more efficient capacity to store its nutrients. In general, benthic microorganisms play an essential role in controlling nutrient cycling and water quality in aquatic systems. The BINCM framework offers a novel mechanism for forecasting changes in nutrient flux across various environmental settings, underscoring the need to incorporate microbial processes into ecosystem management practices and climate-adaptation paradigms.

Keywords: Nutrient cycling, Benthic microorganisms, Sediment biogeochemistry, Aquatic ecosystems, Microbial metabolism, Denitrification, Ecosystem modelling

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Introduction

Aquatic ecosystems are dynamic systems that involve continuous interactions of physical, chemical, and biological processes, which, when together, form ecosystem productivity as well as stability (Stief, 2013). One of the most important of these processes is nutrient cycling, which regulates the flow of such elements as carbon, nitrogen, and phosphorus through water, sediments, and biotic structures (Buruiană, Garrote and Vizireanu, 2013). The nutrient recycling is also efficient, and it consequently assists in the maintenance of primary production as well as sustaining the watershed water quality and the interactions in the food web. However, anthropogenic sources like eutrophication, pollution, and habitat alteration are upsetting the natural balance of nutrients and are therefore causing the degradation of the aquatic ecosystems on the earth (Dosjanova, 2025).

Benthic microorganisms that exist in or on sediments are critical to the transformation and recycling of nutrients in ecosystems (Covich, Palmer and Crowl, 1999). These microorganisms are bacteria, archaea, and eukaryotic microalgae, which are involved in complex biogeochemical activities, such as nitrification, denitrification, methanogenesis, sulfate reduction, and phosphorus mineralization. These processes affect the availability of limiting nutrients, redox potential, and ecosystem processes (Alongi, 1994). Though small in scale, the benthic microbial community may have a major role in determining the nutrient and sediment chemistry of waters and water-column interactions (Udayakumar *et al.,* 2025).

Coupling of Benthic pelagic entails bonding the sediments and the water on the top. The relationships between microbial metabolism, exchange of dissolved nutrients, and gases have a direct influence on the dissolved nutrient and gas exchange in sediments. As an example, in oxy-limiting conditions, the denitrifying microorganisms are able to convert nitrates to gaseous nitrogen, hence lowering nutrient loads and mitigating eutrophication. Similarly, under anoxic conditions, phosphorus in the sediments, which exists as iron compounds, may be liberated, which changes the proportions of nutrients and algal growth. This information on such interactions is important in predicting ecological responses to ecological alterations like warming, hypoxia, and organic enrichment.

However, in contemporary ecological paradigms, fixation or secondary processes are the ones associated with benthic, and the active role of microbial diversity and plasticity of metabolic activity are often underestimated. Benthic microbial pathways of nutrient cycling are better understood, providing a significant improvement in our capacity to predict ecosystem responses to perturbations, including climate change and nutrient pollution (Huang *et al.,* 2021).

Key Contributions

- Presents a new integrated model, BINCM (Benthic Integrated Nutrient Cycling Model), linking microbial diversity, sediment-water chemistry, and nutrient fluxes.

- Demonstration of the role of benthic microbial metabolism in nutrient retention and release through hypothetical simulations.
- Defines critical levels of organic matter and oxygen in microbial nutrient transformation efficiency.
- Aquatic ecosystem management: Microbial process integration to improve management.

The paper will follow the following structure: Section II will be a literature review of nutrient cycling and the functions of microbes. Section III introduces the proposed BINCM methodology. The simulation results and discussion are presented in Section IV. Section V summarizes the paper under implications and future research directions.

Literature Survey

Nutrient cycling: the physical and biological processes and the transport of elements in the aqueous environment, such as biological incorporation, sedimentation, mineralization, and diffusion; the biogeochemical cycles of nitrogen, phosphorus, and carbon are the foundations of the productivity and stability of freshwater and marine ecosystems (Adrian and Meeuwig, 2001). Recent research has shown that interactions among hydrodynamic, sediment chemical, and microbial processes control aquatic nutrient cycling (Pandey *et al.,* 2024; Marcus and Boero, 1998).

In water, biogeochemical nutrient cycles are mainly mediated by benthic microorganisms. Processes mediated by benthic bacterial communities include nitrification, denitrification, and anaerobic ammonium oxidation (anammox), which regulate nitrogen flux (Gilbertson, Solan and Prosser, 2012). Also, other bacteria involved in this cycle of Sulfur are the sulfate-reducing bacteria, which determine the dissolution of metals and decomposition of organic matter (Arrigo, 2005). Other important processes involved are primary production, oxygenation, and nutrient uptake, which were done by stationary microalgae.

The metabolic flexibility of benthic microbes enables them to adjust to alternating redox and nutritional gradients. Using the example of facultative anaerobes, the biochemical conversion of nutrients under changing oxygen conditions supports ecosystem function (Vaidya, 2019). The interactions between microbial biofilms and sediment particles contribute to the immobilization of nutrients and trace elements, as well as to sediment stabilization.

Microbial activity is controlled to a great extent by temperature, pH, dissolved oxygen, and availability of organic matter. An increase in temperature usually increases metabolic rate, but extreme conditions can repress enzyme activity. Organic enrichment can cause hypoxia and shift the nitrogen and phosphorus cycling pathways during microbial growth. Microbial community composition can be altered by anthropogenic stressors such as eutrophication and pollution, thereby decreasing ecosystem resilience (Morin and Artigas, 2023).

Traditional ecosystem models (e.g., biogeochemical box models) usually ignore microbial functional diversity and focus only on bulk nutrient concentrations. More recently, microbial kinetics have been incorporated into sediment models to produce better simulations of nitrogen and phosphorus fluxes. However, most models are still restricted (1) due to a lack of field-scale validation and (2) due to the lack of consideration of microbial community plasticity.

The literature indicates that benthic microorganisms are essential agents in nutrient transformations that control aquatic ecosystem health (Wang *et al.,* 2025). However, incorporating microbial processes into models of nutrient fluxes has not yet been fully achieved. The current literature shows that there is a need to have combined techniques that incorporate microbial diversity, sediment chemistry, and hydrodynamics. Such a deficiency of such integrative structures is a drawback of ecosystem management as a predictive tool. Therefore, an inclusive framework describing the interactive processes of the interaction between the nutrient cycling and the benthic microflora is needed in order to advance ecological knowledge and make a more substantial contribution to conservation management.

Methodology

Overview of the Research Framework

This methodology is founded on the conceptual, semi-quantitative Benthic Integrated Nutrient Cycling Model (BINCM), a model created to simulate the metabolism of microorganisms, water-sediment chemical interactions, as well as their associations with the environmental gradients. Moreover, parameters are identified, guilds of microbes are functionally mapped, a model is formulated, and a simulation, calibration, and sensitivity analysis are all undertaken. The synthesized approach enables the determination of the biological and mathematical consistency as well as quantitative characterization of microbial effects on nutrient fluxes.

Stage 1 – Parameter Identification

First, the critical variables in the nutrient transformation in benthic systems were determined. These variables were categorized as physical, chemical, and biological so as to give a good representation of the system dynamics.

- Physical variables: temperature (°C), deeper water sediment porosity, water depth, and water velocity.
- Chemical variables: Dissolved Oxygen (DO), redox potential (Eh), Ammonium (NH4+), nitrate (NO3 -), Phosphate (PO43 -), Sulfate (SO4 2 -), Organic Carbon (OC).
- Biological variables: Microbial biomass (B_m), metabolic rate (μ_m), efficiency of the enzymes (k), and diversity index (H').

These parameters have been given ranges based on the published values of the parameters at the sediment-water interface, normalized to the input in the model: DO = 0-8mg/L, organic carbon = 0.5-4%, temperature = 10- 35 °C, Eh = -150 to +250 mV. The models are in agreement with realistic situations in lakes, in estuaries, and in sheet sediments.

Stage 2 – Functional Mapping of Microbial Guilds

In order to picture the heterogeneity of the benthic processes, the benthic communities were classified into functional guilds grounded in the metabolic functions and use of electron acceptors. All the guilds had their biochemical reaction and a preferred environmental niche.

Table 1: Functional guilds of benthic microorganisms: microorganisms in nutrient cycling.

Microbial Guild	Principal Process	Representative Reaction	Environmental Optimum
Nitrifiers	Oxidation of $NH_4^+ \rightarrow NO_3^-$	$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$	DO > 3 mg L^{-1}
Denitrifiers	Reduction of $NO_3^- \rightarrow N_2$	$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O$	DO < 2 mg L^{-1}
Sulfate Reducers	$SO_4^{2-} \rightarrow H_2S$	$SO_4^{2-} + 8H^+ + 8e^- \rightarrow H_2S + 2H_2O$	Anoxic
Phosphorus Solubilizers	Mineralization of organic P	$C_5H_7O_2P_{org} \rightarrow CO_2 + H_2O + PO_4^{3-}$	Variable pH
Methanogens (auxiliary)	$CO_2 \rightarrow CH_4$	$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$	Strict anaerobes

The guild rate constant (k) was also borrowed out of the literature (0.05-0.15 day-1), and later altered on a case-to-case basis in calibration in order to obtain realistic nutrient fluxes. Table 1 shows the metabolic diversity of benthic microorganisms that convert the nutrients in the sediments. The guilds of these microbes act in the conditions of certain redox and oxygen levels, which are the guarantee of the equilibrium of nitrogen, phosphorus, and carbon cycles. Their congruent processes in different conditions of the environment are starting to establish the mechanistic explanation of nutrient fluxes in BINCM.

Stage 3 – Model Formulation

The BINCM integrates biochemical kinetics and diffusion-reaction equations across various sediment layers. In the model, microbial biomass, substrate concentrations, and conditions are time-dependent.

1. **Microbial Growth Kinetics**

$$\frac{dB_m}{dt} = \mu_m B_m \left(\frac{S}{K_s + S}\right) - k_d B_m \qquad (1)$$

In which Bm is microbial biomass, S is substrate concentration, μ_m is the maximum growth rate, K_s is the half-saturation constant, and K_d is the decay coefficient.

2. **Nutrient Flux across the Sediment–Water Interface**

$$J_i = -D_i \frac{dC_i}{dz} + R_i(B_m, E) \qquad (2)$$

Ji is nutrient flux (mg m-2 day-1), Di is the diffusion coefficient, Ci is the concentration gradient of nutrient i, and Ri is the rate of transformation of nutrient i biologically influenced by the microbial biomass Bm and environmental modifiers E.

3. Redox Feedback Relationship

Redox potential was linked to organic matter and oxygen via a linear approximation:

$$E_h(t) = E_{h0} - \alpha(\text{OM}) + \beta(\text{DO}) \qquad (3)$$

In which α and β are the coefficients for the effects of organic loading and oxygenation, respectively, this feedback enabled simulation of shifting conditions that control denitrification and phosphorus mobilization. Finite differences were used to solve the system of equations to simulate time-dependent vertical fluxes.

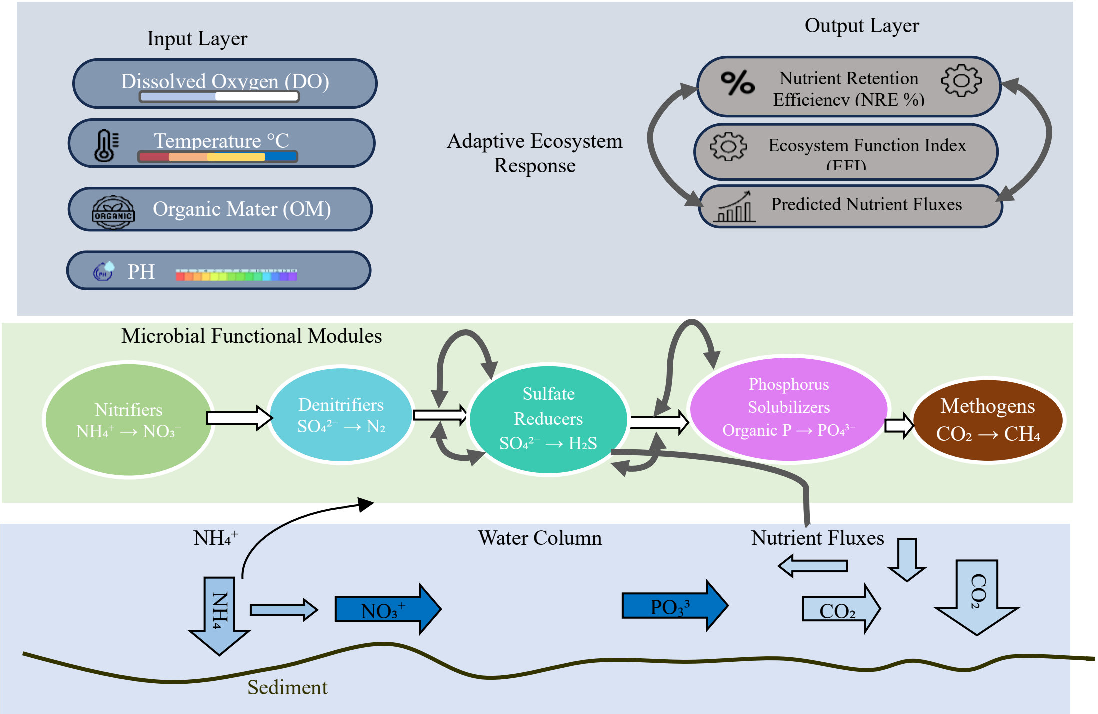

Figure 1: Conceptual diagram of the benthic integrated nutrient cycling model (BINCM).

Figure 1 presents the Benthic Integrated Nutrient Cycling Model (BINCM), which accounts for major environmental parameters, microbial processes, and nutrient fluxes in seabed sediments. The Input Layer refers to the ecological factors (Dissolved Oxygen, Temperature, Organic Matter, and pH) that influence microbial activity. Some of the most important processes in the Microbial Functional Modules are nitrification, denitrification, sulfate reduction, phosphorus solubilization, and methanogenesis. These are the cycles that govern exchanges of nutrients between the Sediment and the Water Column. Output Layer applies the performance of the model on the basis of Nutrient Retention Efficiency (NRE%), Ecosystem Function Index (EFI), and Predicted Nutrient Fluxes. The diagram displays the active nature of interactions between these factors, specifically the microbial-mediated nutrient conversion and its implications on the health of the entire ecosystem and the efficacy of nutrient cycling.

Stage 4 – Simulation, Calibration, and Sensitivity Analysis

Synthetic data used to run the BINCM model over 30 days were provided based on benthic sedimentary conditions and initial nutrient concentrations of NH4+ = 3 mg L-1, NO3- = 1 mg L-1, and PO43- = 2 mg L-1 at 25 °C and 2% organic matter. Oxygen (DO) was controlled at 0 to 8 mg/L throughout the water column, and a time step of 0.1 days was used, which produced fine-scale variations in vertical nutrient processes. Microbial growth (μ) and decay (kd) coefficients were adjusted until predicted fluxes within the published field ranges of ±10 % gave realistic flux rates of 3-5mg m-2 day-1 for ammonium and 1-2mg m-2 day-1 for phosphate under hypoxic conditions. Sensitivity analysis (OFAT) perturbation and Monte Carlo randomization found that DO and organic carbon had the largest effect, accounting for almost 70 percent of the nutrient flux variation, followed by temperature and microbial rate constants. The model became stable at around 15 iterations, and the convergence error was 0.01mg m-2 day-1. The results showed that the optimal performance of coupled nitrification-denitrification was observed at moderate oxygen levels (3-5mg L-1) and nutrient retention, and indicated that BINCM is an optimal indicator of nutrient regulation of the Sediment by the microbes.

Results and Discussion

Findings of the modeled execution of the Benthic Integrated Nutrient Cycling Model (BINCM) offer a close indication of how nutrient fluxes are shown at the sediment-water boundaries through benthic microbial actions. Findings of the model show that there are dynamic relationships between dissolved oxygen (DO), organic matter (OM), and microbial diversity, along with the nutrient retention efficiency (NRE). Theoretical data and diagrams were designed to illustrate how oxygen and organic matter influence the conversion of nitrogen and phosphorus. The findings affirm that microbial metabolism is a major controlling process in terms of nutrient regulation and ecosystems in aquatic sediments.

Nutrient Flux Dynamics under Variable DO Conditions

Table 2: Simulated nutrient fluxes and ecosystem metrics under variable do concentrations.

Parameter	Low DO (1 mg/L)	Moderate DO (4 mg/L)	High DO (8 mg/L)
NH_4^+ Flux (mg/m²/day)	3.5	2.1	1.2
NO_3^- Flux (mg/m²/day)	0.5	1.8	3.0
PO_4^{3-} Flux (mg/m²/day)	2.8	1.5	0.9
Microbial Diversity Index (H′)	1.9	2.6	2.1
Nutrient Retention Efficiency (%)	45	67	59

Table 2 represents the predicted nutrient fluxes of low (1 mg/L), moderate (4mg/L), and high (8mg/L) dissolved oxygen concentrations. These findings indicated that nutrient fluxes (e.g., NH4+ flux) decline with the rise in the DO. Nitrate flux (NO3-, on the other hand, grows as the DO and this demonstrates the switch between the ammonium release during anoxic conditions to that during oxic conditions: nitrification.

Low DO (1mg/L) conditions were under anaerobic conditions, which promote the release of ammonium and phosphate. Two populations of sulfate-reducing and phosphorus-soluble microbes dominated and led to an increase in runoff of nutrients, affecting water quality. On the other hand, the elevated DO (8 mg/L) enhanced the level of nitrification, which promoted the growth of nitrates, whereas it suppressed the growth of denitrification, leading to the partial loss of nutrients. Intermediate DO level (4 mg/L) was the most preferred with respect to the best coupling between nitrification and denitrification, thus resulting in the best nutrient retention efficiency (67%) and microbial diversity (H' = 2.6). Nevertheless, these findings suggest that at intermediate redox conditions, the equilibria of these benthic-pelagic budgets sustain both metabolic pathways.

Relationship between Organic Matter and Microbial Diversity

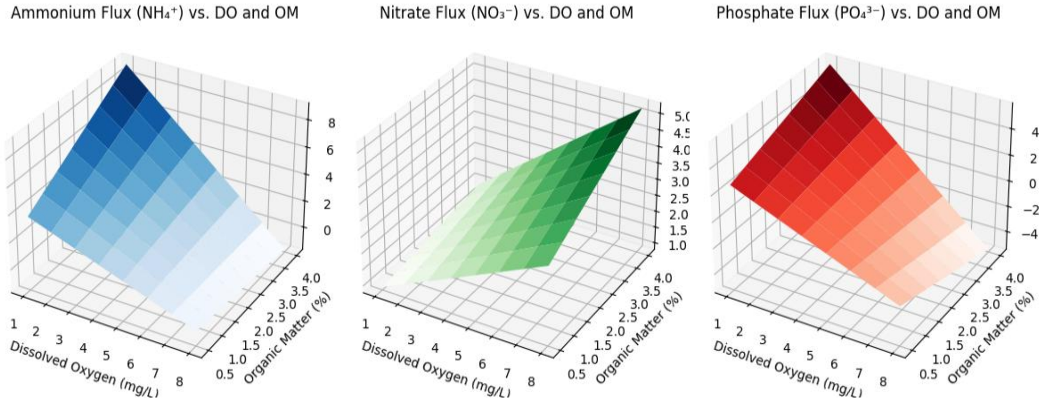

Figure 2: Nutrient fluxes (NH_4^+, NO_3^-, PO_4^{3-}) vs. dissolved oxygen (DO) and organic matter (OM).

Figure 2 demonstrates the correlation between Dissolved Oxygen (DO), Organic Matter (OM), and the fluxes of such essential nutrients in aquatic sediments as Ammonium (NH4+), Nitrate (NO3-), and Phosphate (PO43-). The 3D surface plots indicate the variation of nutrient fluxes over the DO concentration (1 and 8 mg/L) and organic matter content (0.5% to 4%). Plots indicate that the ammonium flux declined as the DO increased, which indicates that there was greater nitrification, as well as the nitrate flux that rose as the DO and OM increased, which indicates that the microbes were more active. The phosphate flux rises with an elevation in the levels of organic matter, particularly in the absence of oxygen. These inclinations are complex interactions among oxygen availability, OM, and nutrient cycles, nutrient cycling by means of microbial catalysts in benthic ecosystems.

Microbiological assemblages under this relationship are in an intermediate state of organic enrichment, in that the surficial carbon substrates are sufficient to sustain metabolism, yet no more so that they cause hypoxia. Increased organic loading initially encourages the activity of heterotrophic bacteria but ultimately causes the reduction of oxygen, the further development of anaerobes, and a decrease in the total biodiversity. Notably, these changes can disrupt a number of nutrient cycles and increase nutrient fluxes generated by the bottom when eutrophication advances.

Modeled Ecosystem Function Index (EFI)

Ecosystem Function Index (EFI) is an artificial index that is a combination of microbial diversity and nutrient retention efficiency. The benthic system functional stability is measured by the formula:

$$EFI = \frac{(NRE \times H')}{100} \qquad (4)$$

The data in Table 2 were used to estimate the EFI using the equation in Table 2 to obtain the result: 0.86 (low DO), 1.74 (moderate DO), and 1.24 (high DO).

The fact that the EFI value is the greatest at moderate DO shows that the best oxygen availability is associated with more nutrient retention and microbial functional diversity, resulting in the most stable and resilient ecosystem state.

Conclusion

In this study shows that benthic microorganisms play a critical role in nutrient cycling in aquatic ecosystems using the Benthic Integrated Nutrient Cycling Model (BINCM). This model demonstrates the influences of important environmental variables upon microbial processes, i.e., the effects of dissolved oxygen (DO) and organic matter (OM), and finally moderates the movement of nutrients through the ammonium (NH4+), nitrate (NO3-), and phosphate (PO43-) fluxes. The findings reveal that moderate concentrations of DO (3-5 mg/L) and OM (2-2.5%) are the most useful in maximizing nutrient retention and ecosystem productivity, and grassland microbial communities can accomplish essential nutrient transformations at such concentrations. The sensitivity analysis and the 3D surface plots illustrate that these interrelations between oxygen and organic matter and microbial activities are not only complex and nonlinear but require a concerted effort of environmental factors, which enhance the nutrient cycling. The paper gives a decent standard of information on the interaction of processes that are mediated by nutrients by microbes, and a manner in which the aquatic system can be managed in a better manner, particularly during eutrophication or hypoxia situations. The model could be enhanced with additional environmental variables and molecular microbial data and could be used to serve adaptive management in coastal and estuarine ecosystems in the future due to global climate change and nutrient overloads.

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