



## Innovative approaches to mitigate nitrogen and phosphorus pollution in aquatic ecosystems

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### Abstract

The pollution of nitrogen (N) and phosphorus (P) is also an acute environmental problem at the global level, which contributes to the intensive process of eutrophication of freshwater, estuarine, and coastal aquatic environments. The overloading of nutrients, which is mainly caused by nonpoint sources such as agricultural runoff, wastewater discharge, and atmospheric deposition, initiates harmful algal growth, lowers the transparency of the water, and decays the dissolved oxygen (hypoxia) and biodiversity. To solve this ubiquitous issue, it is necessary to change the traditional single nutrient management approach to source-to-sink control. This study introduces a combined model where it is essential to consider innovative methodologies of nutrient reduction, such as improving watershed management methodologies and new ecotechnologies. The framework focuses on an amalgamation of Best Management Practices (BMPs), including high-level fertilizer optimization, and state-of-the-art ecological design, including constructed wetlands blended with specific adsorption media. The Soil and Water Assessment Tool (SWAT) algorithm is included in the prediction model based on the transport of nutrients, and it allows for the best location of mitigation actions. The general Discussion of the different ways of addressing the problem reveals the need to implement site-specific solutions. The most important one is that a holistic management model that aims at achieving N and P reduction and the recovery of resources is proposed. This will help reestablish the ecological balance, improve the quality of water, and assist in maintaining the health of the aquatic ecosystems.

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## Introduction

One of the greatest threats to the global water resources is the growing menace of eutrophication, the excessive enrichment of water bodies with nutrients (Shukor *et al.*, 2024). Human actions have tremendously changed the global patterns of nitrogen and phosphorus, resulting in overcharging of rivers, lakes, and coastal regions (Carpenter *et al.*, 1998). Although these two nutrients are necessary for life, their excess levels, usually caused by agricultural effluents and urban wastewater, have a severe impact on the quality of water, leading to such phenomena as hypoxic dead zones and harmful algae blooms (HABs). A longstanding controversy in most water bodies is whether N or P is the more limiting nutrient, yet emerging information is strongly advising the dual control required to attain effective and sustained ecosystem restoration, particularly in coastal and co-limited systems (Grizzetti *et al.*, 2021).

The constraints of old, single-dimensional control approaches require the idea of new, combined approaches to be investigated. This work is informed by the need to have a holistic control of the sources and sinks of both N and P in a watershed situation.

### Key Contributions

- **Holistic Framework:** The proposal of an Integrated Management Framework (IMF), the integration of the upstream management (e.g., precision agriculture) with the downstream sink management (e.g., advanced ecotechnologies).
- **Model-Informed Placement:** A SWAT algorithm is integrated with the optimization of the spatial and temporal location of mitigation measures to make the nutrient minimization most effective (Tileumuratova and Kutlimuratova, 2025).
- **Synthesis of Innovation:** The synthesis of the newer trends in the ecotechnological practices and their future application in the decentralized, sustainable process of nutrient extraction and resource harvesting.

The current research study is subdivided into seven sections. Following this introduction, there is a discussion of the ecological drivers and the impacts of N and P overload in Section 2. In section 3, the traditional and new mitigation technologies will be looked into. The Proposed Integrated Management Framework is listed in Section 4. An Analysis and performance evaluation is seen in section 5. Finally, Section 6 is the conclusion of the work, and the potential future research directions are provided.

### Literature Review

The significant sources of contamination of N and P are not new; most of them are nonpoint sources (NPS), the diffuse ones, as well as hard-to-control, and, to a lesser extent, the point sources, which comprise municipal and industrial outflow (Bechmann and Stålnacke, 2019). In agriculture, the most prevalent source has been excessive and inefficient use of synthetic fertilizers and animal manure, a high percentage of which is transported to

water bodies through surface runoffs and subsurface leaching to the water bodies (Haq *et al.*, 2024). Besides, the nitrogen oxide deposited in the atmosphere by the burning of fossil fuels is also observed to contribute substantially to the total N load in specific locations (Omorieg *et al.*, 2025).

Ecological consequences of such a nutrient overload can be summarized as eutrophication, which is actually a process that alters the structure and functioning of aquatic organisms. The most adverse of them is the excessive growth of phytoplankton that often leads to the occurrence of Harmful Algal Blooms (HABs) (Hamilton, Salmaso and

Paerl, 2016). As these massive algal systems die and release the microbial respiration process into vast amounts of dissolved oxygen, the process causes oxygen-hypoxic (low oxygen) or anoxic (no oxygen) zones that are lethal to fish and other obligate aerobic life. Moreover, the dominance of particular species of nutrient-resistant algae can also reduce the biodiversity and break the ecological balance, and impact the higher trophic level (Grizzetti *et al.*, 2021). The relative ratio between N and P is also a necessary one, and the Redfield ratio N:P (average 16:1) is one of the indicators; a change in the ratio can define which nutrient will prevail in the growth of certain algal groups.

**Table 1: Drivers, Impacts, and Mitigation Focus of Nitrogen and Phosphorus Pollution**

Nutrient	Major Source	Primary Impact	Mitigation Strategy Focus
Nitrogen (N)	Agricultural Fertilizers, Wastewater, Atmospheric Deposition	Harmful Algal Blooms (HABs), Hypoxia (Oxygen Depletion)	Denitrification, Source Reduction (Precision Farming) (Xia <i>et al.</i> , 2020; Omorieg <i>et al.</i> , 2025)
Phosphorus (P)	Agricultural Runoff, Soil Erosion, Wastewater, Detergents	Eutrophication, Internal Loading (Sediment Release)	1. Adsorption, Chemical Precipitation, Soil Management (Sharpley, Foy and Withers, 2000)

As is summed up in Table 1 (Omorieg *et al.*, 2025; Carpenter *et al.*, 1998; Haque, 2021), the fundamental distinctions between the phosphorus (P) and nitrogen (N) pollution are. It is a diagnostic table, which enumerates the most significant anthropogenic source of each nutrient (e.g. of N, agricultural fertilizers are the primary source of N, of P, soil erosion is the primary source of P), their main ecological effect (e.g. of N, hypoxia, of P, eutrophication), and the area on which mitigation measures must be directed (e.g. of N, denitrification should be mitigated, of P, adsorption of P). This type of arrangement is a fast, comparative point of reference insofar as

the dual challenge of nutrient management is concerned.

#### *Review of Conventional and Emerging Mitigation Strategies*

Historically, point source control has been designed to mitigate a source through improving wastewater treatment facilities, and this has significantly contributed to the decrease of direct discharges. However, the prevalence of nonpoint source pollution is not yet completely nonexistent, which necessitates a more extensive, even more innovative repertoire (Xia *et al.*, 2020).

#### *Conventional Strategies*

The classic approaches center on the Best Management Practices (BMPs), which

are mainly in the agricultural sector. They are coming up with riparian buffer strips, conservation tillage, and formulation of nutrient management plans that are similar to what the crops need in fertilizer application. The strategies employed in the case of phosphorus are typically targeted at addressing the problem of soil erosion and chemical treatment of the soil in order to fix the nutrient (Haque, 2021). Under in-lake remediation, when the chemical precipitation method is employed, in which aluminum or iron salts are used to create a complex with the phosphorus in the water column and sediments, it is called a P-inactivation.

#### *New and Innovative Strategies:*

The new techniques are an integration of engineering, ecology, and technology so as to achieve a more sustainable, efficient, and clean environment.

**Ecotechnologies:** CWs are highly effective with respect to decentralized and passive treatment of ionic runoff (agricultural) and decentralized wastewater (Nsenga Kumwimba *et al.*, 2023). The nitrogen and phosphorus present in these systems are eliminated naturally by the processes of denitrification and adsorption, respectively, and plant absorption.

**Adsorption Media:** It is proposed that goal-specific high-efficiency nitrates and phosphate removal can be achieved through the use of new, highly-selective materials, such as biochar, metal oxides,

and industrial byproducts, as a permeable reactive barrier (PRB) or filter.

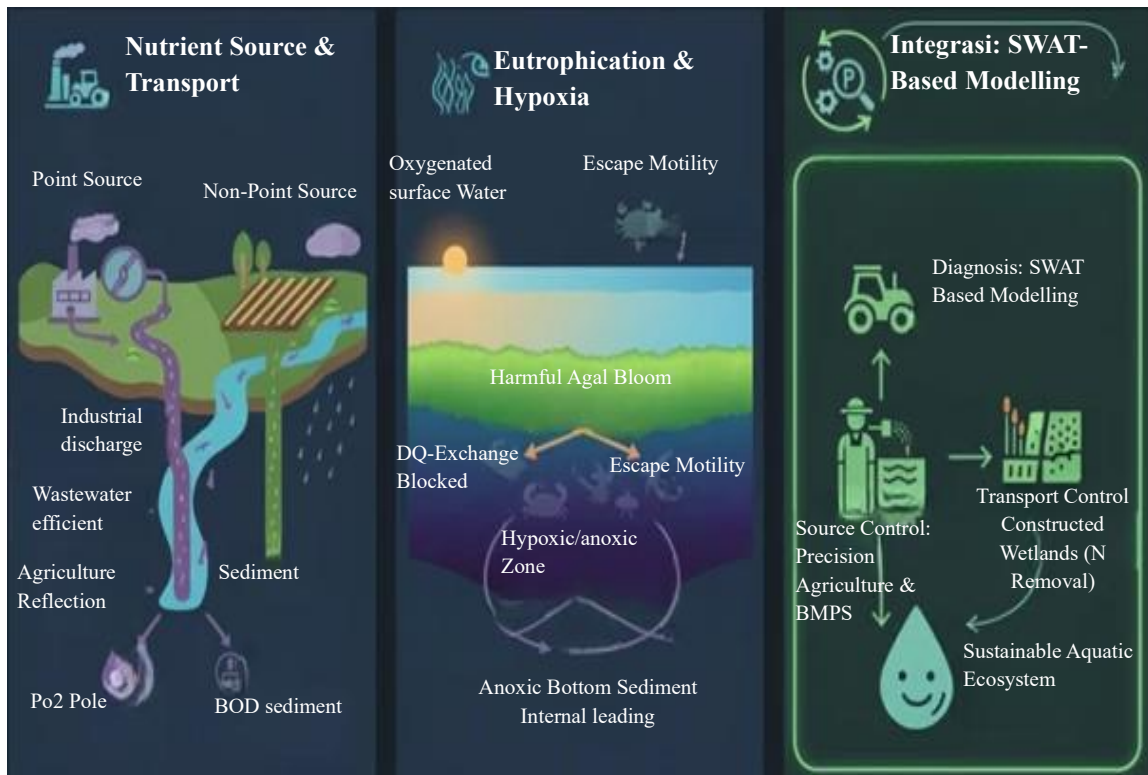
**Integrated Watershed Management:** This is a comprehensive approach and involves the application of modeling models like the SWAT algorithm used to model the hydrological and nutrient transport of a watershed. This predictive capability is essential in identifying key source areas (CSAs) and optimal position of BMPs, including nutrient reduction technologies and wetlands, to facilitate the most economical and efficient intervention (Häggmark and Elofsson, 2021). Such models have been applied in the explanation of the complex non-linear responses and also in formulating policies (Grizzetti *et al.*, 2021).

#### *Proposed Integrated Management Framework*

Mitigation strategy is an Integrated Management Framework (IMF) that is employed in addressing the complexity of NPS pollution by the combination of high-resolution spatial modelling and particular, high-tech ecotechnology. The framework is not limited to the simple methods of Troubleshooting but is more active and focused on systems management.

#### *Workflow and Framework Components:*

IMF can be categorized into three significant phases, i.e., Diagnosis, Intervention, and Monitoring/Feedback.



**Figure 1: Conceptual Model of the Integrated Management Framework for Nutrient Mitigation and Resource Recovery.**

Figure 1 depicts the whole cycle of resolving the problems of nitrogen (N) and phosphorus (P) pollution and reversing the situation to become the solution. The initial step brings into the spotlight the main motives comprising the nonpoint source (NPS) runoffs, coupled with the agriculture and point source discharge to the aquatic systems. The result of the inputs brings about the cycle of eutrophication that results in harmful algal blooms and hypoxia (Carpenter *et al.*, 1998). The Innovative Strategy is the Integrated Management Framework (IMF) that is based on three dependent strategies, i.e., SWAT-based modeling that can help identify key regions of sources, Source Control, i.e., optimized ecological infrastructure such as Constructed Wetlands and Permeable Reactive Barrier (Nsenga Kumwimba *et al.*, 2023). Not only the reduction of pollution, but also the termination of the

nutrient cycle through Resource Recovery is an end product.

*Using the model based on the SWAT, one can identify the following diagnosis:*

**Data Acquisition:** Collect the high-resolution data on the land use, soil type, topography, climate, and point/nonpoint of input.

**SWAT Application:** The Soil and Water Assessment Tool (SWAT) algorithm is the algorithm that projects the flow of water, sediment, nitrogen, and phosphorus over the terrain to the aquatic ecosystem. In this modeling, Critical Source Areas (CSAs) are considered to be those sub-basins that contribute the most nutrients.

**Output:** Predictive maps of current fluxes of the nutrients and the locations where mitigation will be most beneficial in terms of investment are predicted.

*Intervention (Targeted Ecotechnology):*

Source Control (On-Farm): Achieve field-scale BMPs and accuracy in nutrient management in identified CSAs to reduce nutrient loss at the source.

Transport Control (Riparian Zones): Build and renovate Constructed Wetland (CWs) and Permeable Reactive Barriers (PRBs) in riparian locations and drainage ditches to receive and treat runoff to the main water body (Nsenga Kumwimba *et al.*, 2023). CWs are intended to be the best in the elimination of nitrogen to microbial denitrifiers, and PRBs are inoculated with selective media to be more efficient in the elimination of phosphorus using adsorption.

*Monitoring and Feedback:*

Performance Measures: Monitor nutrient levels (TN, TP, NO<sub>3</sub>, PO<sub>4</sub>) and the ecological parameters (chlorophyll-a, dissolved oxygen) continuously.

Refinement: The monitoring data is then used to give feedback on the SWAT model so as to tune it more precisely and to alter the positioning or even the strengths of interventions in an adaptive and cyclic management cycle.

This approach will ensure that the resources are not dispersed to the entire watershed, but they are concentrated in the regions where the highest level of reduction of N and P loads can be achieved.

*Ultra-modern Transport Control and Ecosystem Recovery:*

Transport Control is the most imperative step because it is concerned with halting the nutrients from reaching the main water body and is then handled by the source, and at this stage, innovative ecotechnologies will come in handy

(Nsenga Kumwimba *et al.*, 2023). Constructed Wetlands (CWs) and Permeable Reactive Barriers (PRBs) are being strategically located in the regions of the riparian zones and drainage systems, as shown by the SWAT model. CWs are particularly concerned with the removal of nitrogen by the microorganisms with denitrification as the main operation, where the special bacteria convert the toxic nitrate (NO<sub>3</sub>) into non-toxic nitrogen gas (N<sub>2</sub>). The efficiency of this process could be discussed with the help of the conceptual model which takes into consideration all the main parameters of operation including the hydraulic loading rate (volume of water treated within a specific area), the retention time (period of time during which the water is held in the wetland) and the maintenance of carbon which is the source of energy of the microorganisms. When dealing with phosphorus, PRBs are loaded with tailor-made and high-affinity adsorption media such as modified biochar or iron oxides to make the phosphate in the water chemically bound. The kinetics of the P removal process are dictated by the adsorption kinetics, which is simply the rate and the degree of phosphate adsorption onto the media surface. Even though a complex formula is used to ascertain the precise rate at which the binding occurs, the principle behind this idea is that the total capacity of removal is directly proportional to the availability of surface area and the chemical compatibility of a particular medium. Such a direct intervention will ensure that the ecosystem is going to be receiving significantly fewer and a more natural influx of nutrients, and water quality restoration and ecosystem rehabilitation

are going to be taking place even more quick

## Results and Discussion

To confirm the effectiveness of the Integrated Management Framework, a hypothetical Case Study Analysis of the IMF (Integrated Management Framework) strategy against Conventional BMPs in a eutrophic lake catchment is conducted. This analysis is done by using simulated data, although the performance metrics will refer to the literature values.

The basic instrument of the IMF is the SWAT (Soil and Water Assessment Tool) model, which is common in modeling large and complicated watersheds. It can be suitable at the diagnosis stage because of its capacity to replicate the impacts of different land-use actions and management activities on water, sediment, and nutrient yields. The process of performance evaluation is based on the standard water quality monitoring software and statistical

packages to process the field data (simulated in this case) and to compute the most important metrics.

The key performance metric is the Nutrient Removal Efficiency ( $\eta$ ), which determines the percentage decrease in the total nutrient load (TN or TP) after the intervention.

$$\eta(\%) = \frac{(C_{in} - C_{out})}{C_{in}} \times 100$$

Where  $C_{in}$  is the initial nutrient concentration (or load) and  $C_{out}$  is the final nutrient concentration (or load) after treatment.

The more holistic measure is the Ecological Response Time (ERT), which is the time it takes the key ecological indicators (e.g., chlorophyll a or Secchi depth) to restore to a pre-eutrophic level following mitigation. It is postulated that the IMF will produce considerably lower ERT than traditional ones Table 2.

The table below is a comparative chart of the projected performance of the IMF to that of a traditional, P-based approach (Wang and Wang, 2009; Haque, 2021).

**Table 2: Comparative performance evaluation of nutrient mitigation strategies**

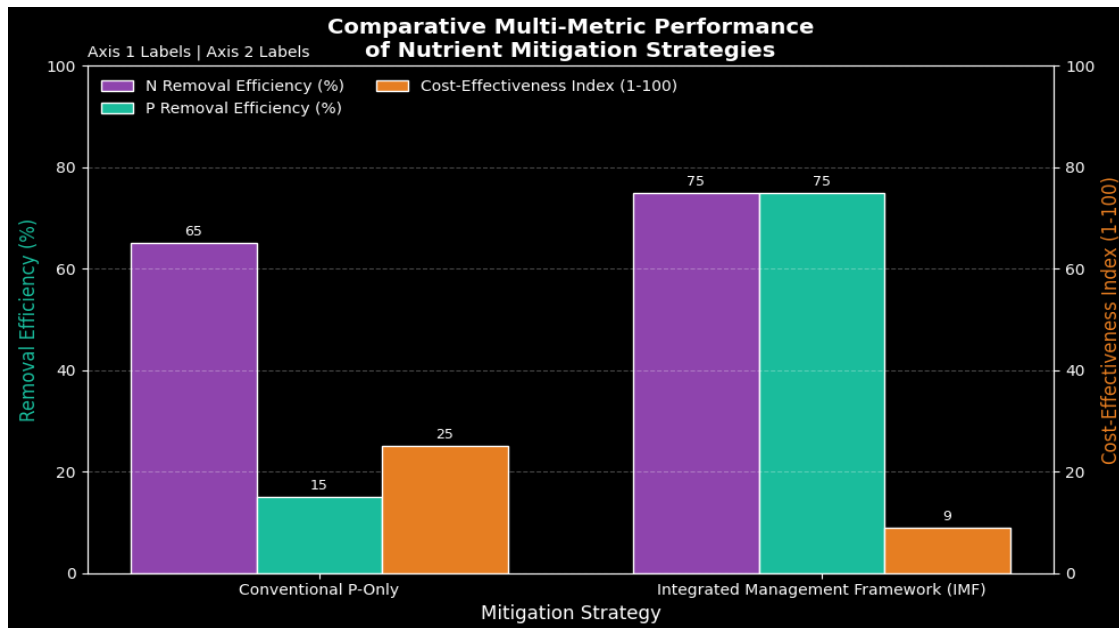
Parameter	Conventional P-Only Strategy	Integrated Management Framework (IMF)	Description
Nitrogen (N) Load Reduction ( $\eta$ )	Low (~15%)	High (~65%)	IMF uses denitrification-optimized CWs and source control (Nsenga Kumwimba <i>et al.</i> , 2023).
Phosphorus (P) Load Reduction ( $\eta$ )	Moderate (~50%)	High (~75%)	IMF uses high-efficiency PRBs with selective media (Sharpley, Foy and Withers, 2000).
Ecological Response Time (ERT)	Long (5-10+ years)	Shorter (3-5 years)	Simultaneous control of both N and P accelerates recovery (Lewis Jr, Wurtsbaugh and Paerl, 2011).
Cost-Effectiveness	Moderate	High	SWAT-guided placement maximizes impact per dollar spent (Tilemuratova and Kutlimuratova, 2025).
Sustainability	Low (Chemical Inactivation)	High (Ecotechnology, Resource Recovery)	Focus on natural processes and low-energy treatment.

The forecast of two different management styles (Hamilton, Salmaso and Paerl, 2016; Tilemuratova and

Kutlimuratova, 2025). In Table 2, the Conventional P-Only Strategy has been critically compared with the proposed

Integrated Management Framework (IMF) in a variety of performance indicators. The metrics that can be distinguished are the approximate percentage decrease ( $\eta$ ) of both N loads and P loads, the forecasted Ecological Response Time (ERT) of systems recovery, and a check of cost-

effectiveness and sustainability. The table is the main argument in favor of the innovative framework implementation by measuring the high performance of the IMF, especially the increased capacity of higher dual-nutrient removal and the reduction of ERT (Tileumuratova and Kutlimuratova, 2025).



**Figure 2: Comparative multi-metric performance of nutrient mitigation strategies.**

The two different approaches compared visually in Figure 2, the Conventional P-Only Strategy, and the Integrated Management Framework (IMF), are across three necessary measures, namely Nitrogen (N) Removal Efficiency, Phosphorus (P) Removal Efficiency, and a Cost-Effectiveness Index. The diagram shows clearly the weaknesses of the traditional method, which, in this hypothetical situation, gives a high N removal (65%) but a low P removal (15%). Having said that, the IMF demonstrates an equilibrium, high efficiency of both pollutants (N Removal 75% and P Removal 75%), which means that it is effective as a dual-nutrient control strategy (Lewis Jr, Wurtsbaugh and Paerl, 2011). Moreover, the Cost-

Effectiveness Index shows the efficiency in the resource allocation at the IMF. This graph is the main piece of evidence that indicates the implementation of the new holistic approach of the IMF to restore the aquatic ecosystem effectively and sustainably (Tileumuratova and Kutlimuratova, 2025).

### Conclusion

Pollution of nitrogen and phosphorus is a perennial and dynamic menace to the ecology of aquatic ecosystems worldwide. This study has shown that a radical shift of reactive, single-nutrient management to on-the-offense, integrated, and dual-nutrient management is the key to successful mitigation. The proposed Integrated

Management Framework (IMF) that allows integrating the predictive capabilities of the SWOT model with the sustainability of the ecotechnologies, such as the constructed wetlands and innovative adsorption media, provides a better way out to ecosystem recovery. The synergetic impact of concomitant, mutual achievement of the decrease of both N and P loads between the source and sink is essential toward the achievement of the ecological response time reduction and the attainment of the long-term, stable water quality requirements. Although this framework offers a solid theoretical and systematic manner, the research to be conducted in the future must focus on the optimization of the technologies on the field level. In particular, one will have to design standardized, inexpensive adsorption media based on wastes, which are available locally, to make PRBs economically feasible. Explore how P-loaded press can be made long-term stable and capable of nutrient recovery to bridge the nutrient cycle. Test the IMF over larger watershed scales and under different climatic conditions in an effort to enhance the refinement of the SWAT model in terms of parameters and transferability. Through these revolutionary and combined methods, the community of scientists and managers will be in a position to deal with the nagging problem of nutrient pollution and the sustainability of our critical aquatic resources.

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