Integrated ecological and technological approaches for nutrient removal from anthropogenically polluted surface water: a case study of Burgas Lake (Vaya Lake)

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Abstract. Declining water availability, eutrophication and increasing anthropogenic pressure on aquatic ecosystems highlight the need for sustainable approaches for nutrient reduction and safe water management.

This study evaluates a pilot, multi-stage filtration system as a possible additional step for the further treatment of water. Two experimental filtration units were tested with water from Burgas Lake (Vaya Lake), as the lake is highly anthropogenically polluted: a filter containing natural zeolite (clinoptilolite) and a filter with biomass from the macrophyte *Stuckenia pectinata*. After 60 minutes of recirculation, a reduction of TN (Total Nitrogen) to 67-76%, of $N\text{-}NO_3$ (Nitrogen Nitrate) to 19-38% and of PO_4^{3-}- P (Orthophosphate) to 58-66% was observed.

The results show that both nature-based filtration media effectively reduce nitrogen and phosphorus compounds under controlled laboratory conditions, with a higher nutrient removal efficiency observed for the *Stuckenia pectinata* filter. The proposed pilot system can serve as a preliminary modelling framework for further treatment of anthropogenically polluted surface waters and for future development of risk-based water management approaches.

Keywords: ecological approaches, nutrient removal, Burgas Lake.

1. Introduction

In the context of increasing water scarcity in Europe and increasing droughts, securing safe and sustainable water sources is becoming a critical challenge for agriculture. Demographics, climate change and intensive use of water resources are leading to a serious shortage of available supplies of clean drinking water and water for irrigation purposes (Cammalleri et al., 2021).

In this context, the development and implementation of innovative technologies, combined with classical methods and technologies, are essential to ensure sustainable water resources and support the agricultural sector (Motta et al., 2025).

As early as 2012, the European Union identified water reuse as an important, but still insufficiently realized, opportunity to address the growing challenges of water scarcity, eutrophication and drought (European Commission, 2012).

At EU level, only treated urban wastewater is explicitly allowed for reuse in agriculture, according to (Regulation (EU) 2020/741). In parallel, the Water Framework Directive (Directive 2000/60/EC) emphasizes the protection and improvement of the ecological and chemical status of surface and groundwater bodies, highlighting the importance of measures aimed at reducing nutrient pollution and preventing the deterioration of aquatic ecosystems, and rainwater is promoted as a sustainable source in the EU's circular economy and climate change adaptation strategies (Szołdrowska et al., 2025).

Over the last decade, more and more countries have considered the use of reclaimed water for irrigation as a means of ensuring and increasing agricultural production (Abou-Shady et al., 2023). In Bulgaria, the majority of urban wastewater treatment plants (WWTPs) apply primary and secondary treatment, while tertiary treatment is not widely implemented and is applied only in a limited number of plants and under specific conditions (European Environment Agency, 2024; National Statistical Institute, 2024).

Although legislation allows the reuse of treated wastewater for irrigation, this practice has not been implemented due to the lack of the necessary infrastructure, high investment costs, absence of economic incentives and regulatory mechanisms. This is also contributed by the many available water resources, which in turn leads to a decrease in the interest of treatment plants and agricultural producers in implementing water treatment systems (SUWANU Europe, 2021; Ministry of Environment and Water, 2024; Global Water Partnership, 2022).

In countries such as Spain, Italy, and Israel, where water reuse in agriculture is an established practice, treated urban wastewater undergoes tertiary treatment explicitly designed for nutrient removal (primarily nitrogen and phosphorus), in line with Directive (EU) 2024/3019, and is subsequently stored in open reservoirs that function mainly as hydraulic buffers to ensure a continuous water supply. In many cases, no further treatment is applied prior to irrigation (Maffettone & Gawlik, 2022). This operational practice does not fully account for potential risks associated with secondary contamination, microbial regrowth, and physicochemical alterations of nutrient concentrations during storage (Jjemba et al., 2010).

To ensure environmentally sustainable management of anthropogenically polluted surface waters, additional polishing and nutrient reduction processes may be required in systems exposed to excessive nutrient loading (Florides et al., 2024). In this context, nutrient removal is not intended to eliminate essential elements for ecosystem functioning, but to mitigate eutrophication risks associated with elevated nitrogen and phosphorus concentrations, which can lead to algal blooms, oxygen depletion, and ecological imbalance. Therefore, the objective is the restoration of water quality to ecologically acceptable levels, ensuring safe reuse (e.g., for irrigation) without inducing downstream environmental degradation.

One of the promising strategies to address the problem is the application of natural adsorbents, which are low-cost, environmentally safe and effective in retaining various types of pollutants in water (Mihai et al., 2025) (Fig.1).

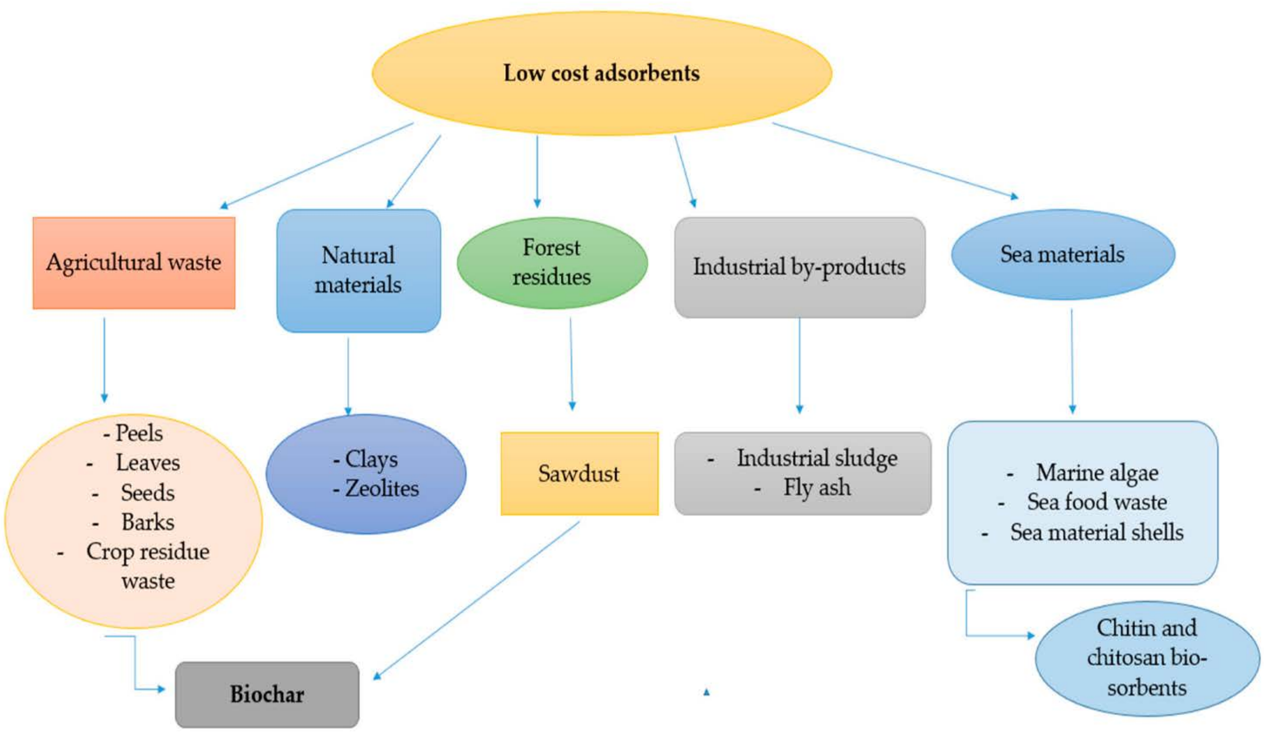

Figure 1. Low-cost organic waste compounds used as adsorbents for dyes removal (Mihai et al., 2025).

Zeolites possess these properties and are considered to be particularly promising and economically advantageous adsorbents (Eberle et al., 2022). Clinoptilolite is a natural zeolite with a cation exchange capacity (CEC) in the range of 100-200 meq/100g (1-2 meq/g), exhibiting particular selectivity towards ammonium ions. Bulgarian clinoptilolite from the Beli Plast deposit has high purity (85-90%) and a CEC of about 1.6-1.8 meq/g, making it one of the most effective in Europe for removing NH_4+ and heavy metals (Shoumkova, 2011). Modified forms of clinoptilolite also demonstrate significant capacity for removing nitrate (up to 63%) and phosphate ions (up to 39%) from aqueous media (Sadeghi et al., 2021).

The search for innovative solutions and technologies for water treatment draws the attention of scientists to the application of aquatic macrophytes, which play an essential role in the self-purification processes of aquatic ecosystems, (De et al., 2019). They are higher aquatic plants with a well-developed photosynthetic system and high sorption and biotransformation capacity with respect to various pollutants from the aquatic environment (Maranho & Gomes, 2024); (Syulekchieva et al., 2024).

Among the macrophytes with proven potential for water purification is Stuckenia pectinata (sago pondweed) (Petrů & Vymazal, 2018). The species is characterized by a high growth rate, a large area of contact with water, and the ability to accumulate significant amounts of nutrients and heavy metals without visible signs of toxicity (Malea et al., 2021).

Experimental studies have shown that Stuckenia pectinata can remove up to 70-80% of Fe, Cu, and Pb, and over 50% of nitrate nitrogen and phosphate from water samples in laboratory conditions and under specific conditions (Singh et al., 2014).

Aquatic macrophytes are considered biological equivalents of natural adsorbents, which combine physicochemical capture with biological uptake. This makes them particularly promising and environmentally sustainable phytoremediators, suitable for application in systems for natural treatment of wastewater and stormwater, buffer zones and artificial wetlands (Kola et al., 2025).

The aim of this study is to evaluate the feasibility of polishing anthropogenically impacted surface water through a modular filtration system incorporating two novel filtration units based on natural zeolite and the aquatic macrophyte *Stuckenia pectinata*. The system is tested using eutrophic lake water as a model surface water matrix, to simulate realistic conditions of nutrient-enriched freshwater bodies. The assessment is based on nutrient removal efficiency as a key indicator for mitigating eutrophication-related risks and improving water quality for potential safe agricultural reuse.

2. Study Area

In this study, a water sample from Burgas Lake (Vaya Lake), Bulgaria, with geographic coordinates (42.493123, 27.344237) was used, due to the fact that the lake is highly anthropogenically polluted (Fig.2).

Figure 2. The Study Area

According to the (Basin Directorate Black Sea Region, 2022), industrial wastewater is discharged into the lake from several point sources. In addition, two wastewater treatment plants operate in the region, and diffuse pollution originating from agricultural, transport and livestock activities also exerts an additional burden on the ecosystem.

2. Materials and Methods

To assess the efficiency of surface water treatment, a modular treatment system was used, the configuration and technical characteristics of which are described in detail in a previous study by the authors (Syulekchieva et al., 2025). An experiment was conducted in two stages of operation under similar conditions in order to assess the adsorption potential of each individual filter.

The first stage included a filter containing 200g of natural zeolite (clinoptilolite) with the trademark AIZEO, originating from the Beli Plast deposit, Bulgaria (Fig.3A, filter 2). The second stage used a filter containing 10g of unfragmented dried biomass of the macrophyte *Stuckenia pectinata*, collected from Burgas Lake in June 2025 (Fig.3B, filter 2). The sample was pre-soaked in distilled water for 24 h, at room temperature, the aim being to remove residual nutrients (Garbowski, 2019). The procedure was considered complete when the measured concentrations were below the limit of quantification of the relevant analytical methods.

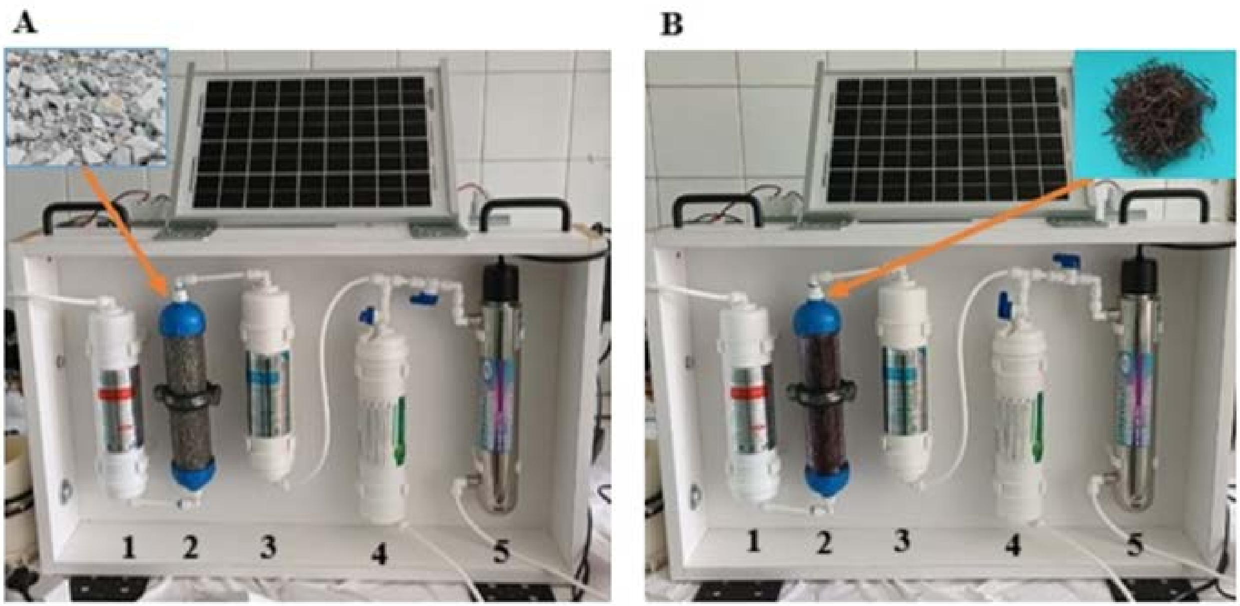

Figure 3. Photos of a modular purification system with two different filters: A-2 with a zeolite filter, B-2 with a *Stuckenia pectinata* filter.

A 2L water sample was circulated through the system using a water pump for 60 min, with a filtration rate of 2.66 x 10^{-4} L/min. Filtration was performed in the following sequence indicated in Fig. 3, A): 1- linear mechanical filter - PP-1μk-QC; 2- zeolite filter; 3- linear activated carbon filter - GAC-QC-2.0; 3- S-HM ultrafiltration membrane; 5- UV sterilizer and, respectively, in the analogous Fig. 3, B) a filter with *Stuckenia pectinata* was installed in the second position.

Sample preparation includes subsequent filtration through a 0.45 μm syringe filter and standard laboratory analysis according to the described methods. For the needs of the experiment, a DR 3900 Hach ® spectrophotometer was used together with cuvette tests LCK238 total nitrogen (TN), LCK339 for nitrate nitrogen (N-NO_3) and LCK 349 for orthophosphate (PO_4^{3-}- P) determination. The remaining physicochemical parameters: pH, dissolved oxygen, temperature, salinity, TDS (total dissolved solids), electrical resistance and electrical conductivity were measured with a portable multimeter WTW Multi 3630 IDS (Tabl.1).

4. Results

To evaluate the efficiency of the two filtration configurations, nutrient concentrations were compared before and after the 60-minute treatment cycle. Significant reductions in TN, N-NO_3, and PO_4^{3-}- P concentrations were observed following ultrafiltration in both systems (Fig. 4) The filter containing *Stuckenia pectinata*, demonstrated comparatively higher removal efficiency, reaching 76.27% for TN and 66.13% for PO_4^{3-}- P, while nitrate nitrogen (N-NO_3) removal reached 37.87% (Fig. 5).

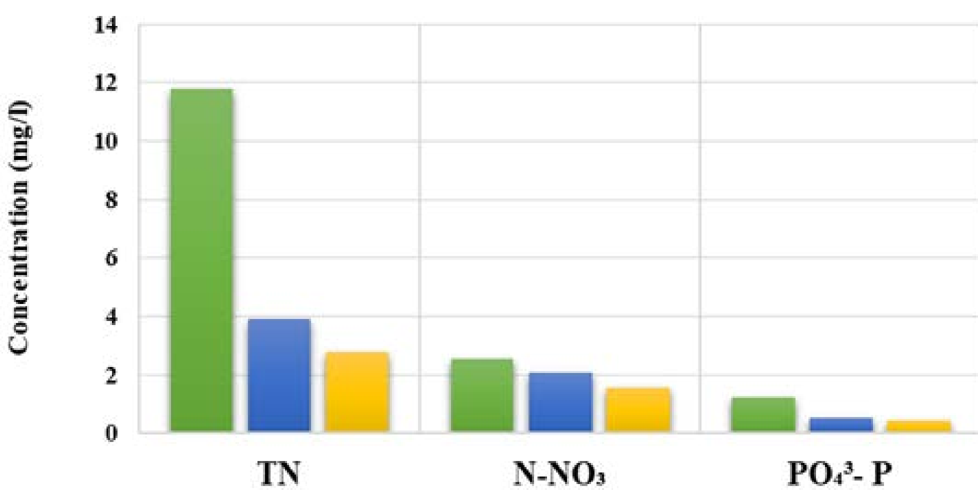

Figure 4. TN, N-NO_3 and PO_4^{3-}- P concentrations before and after the 60-minute treatment cycle with the zeolite (clinoptilolite) and *Stuckenia pectinata*

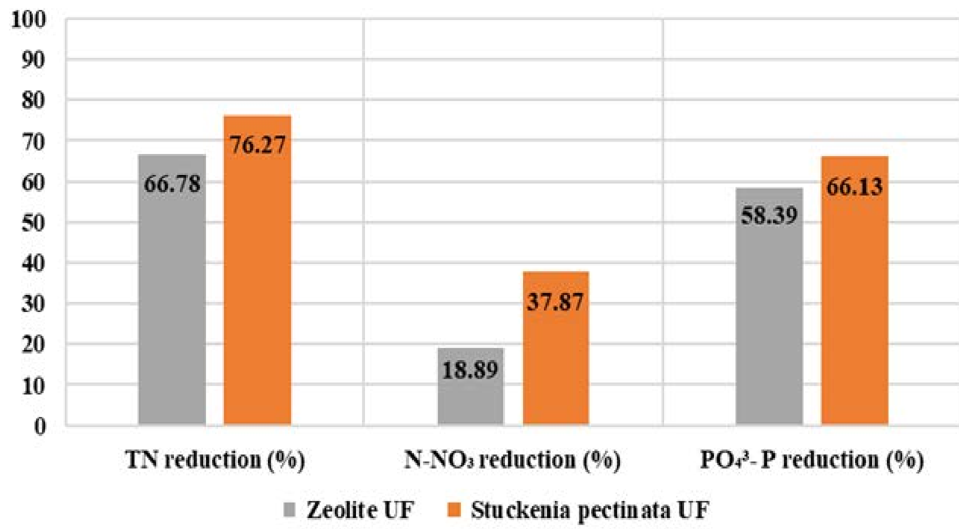

Figure 5. Reduction efficiency (%) of TN, $N–NO_3^-$, and PO_4^{3-}–P after a 60-minute treatment cycle

Table 1. Values of the measured basic physicochemical parameters before and after filtration.

Samples	Total Dissolved Solids (mg/l)	Conductivity (µS /cm)	Salinity (‰)	Specific Electrical Re. (ρ Ω.cm)
Water sample from Burgas Lake	1325	1325	0.6	420
Zeolite (clinoptilolite) after 60 min ultrafiltration	1114	1114	0.5	894
***Stuckenia pectinata* after 60 min ultrafiltration**	930	930	0.4	1076

5. Discussion

The results show higher adsorption efficiency at short contact time (60 min), compared to those reported by (He et al., 2017), where a hybrid zeolite-slag substrate achieved approximately 20 % PO_4^{3}- P removal, and 30% TN removal from the filtrate.

Regarding phosphorus removal, the zeolite filter demonstrated an efficiency of 58.39 %. This result is consistent with the observations of (Choi et al., 2012), who reported unmodified clinoptilolite exhibits limited phosphate adsorption capacity and becomes saturated relatively quickly, reaching approximately 0.15 mg P/g zeolite within the first 24 h.

Asmellash & Ayele, 2022, used bimetallic Al/Cu-modified natural zeolite (Z-Al/Cu), for the removal of phosphates (PO_4^{3-}- P) from aqueous solutions, showing significantly higher adsorption efficiency than the unmodified zeolite (Asmellash & Ayele, 2022). The maximum phosphate removal reaches 99.32% at a contact time of 60 minutes, pH=2 and an initial phosphate concentration of 25 mg/l. (Castro et al., 2021) in a field test of a zeolite (clinoptilolite)-based nutrient capture system (NCS) for ammonium removal from highly concentrated blackwater in a non-canalized sanitation system, found that the NCS was able to remove 80 ± 28%, 64 ± 23%, and 94 ± 11% of the incoming ammonium during three loading cycles.

In a study by (Mažeikienė & Šarko, 2023), a prototype of the NCU (Nutrient Control Unit) of the additional wastewater treatment plant was developed, reducing by 86.3% phosphorus compounds in wastewater and 82% nitrogen compounds with a filter medium of zeolite (clinoptilolite) and quartz sand with a coating formed by Fe, Mn and Ca oxides, studied at time intervals for a 4-month period.

Although there is no literature data for a similar experiment with dried biomass of *Stuckenia pectinata*, there are data for species with similar chemical functionality and adsorption mechanism of the studied species. For example, a study by (Erfanifar & Aminikhoei, 2020) with dried biomass of *Sargassum ilicifolium* reached 71.8% phosphorus removal at 60 minutes and pH=2, in a similar study by (Barrios et al., 2025), at the same contact time, *Arthrospira platensis* biomass achieved results of 88% phosphate removal at pH=7, from aqueous solutions, which is analogous to the present study 66.13% removal of PO_4^{3-}- P, in 60 min.

Temperature slightly affects sorption, but the main differences in purification efficiency are due to the specific properties of the sorbents (Ho & McKay, 1999; Priya et al., 2022). Optimal pH (~7–7.5) enhances nitrate and phosphate removal by stabilizing surface charge and activating sorption sites (Volesky, 2007; Alagha et al., 2020). Dissolved oxygen does not significantly influence sorption, as the mechanisms of clinoptilolite and non-living biomass are electrostatic and independent of redox conditions (Wang & Chen, 2009). Total Dissolved Solids (TDS), electrical conductivity and salinity reflect the total mineralization and ionic strength of the solution, which determine the degree of competition between non-selective anions and target anions (N-NO_3, PO_4^{3-}- P), in adsorption processes on inert (non-living) sorbents (Chouyyok et al., 2010). In clinoptilolite, the reduction of TDS is mainly due to cation exchange between the structural metal cations of the mineral (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}) and dissolved ions. As a result, part of the dissolved cations are retained in the porous structure by exchange, which reduces the total ionic concentration in the solution (Misaelides, 2011). In the non-living biomass of *Stuckenia pectinata*, the significant decrease in TDS could be explained by the presence of deprotonated carboxyl and phenolic groups, capable of binding anions and dissolved organic molecules, which expands the sorption mechanism of the biomass to capture a wider range of ions, especially phosphorus forms (Stumm & Morgan, 1996). The specific electrical conductivity (ρ Ω.cm) is inversely proportional to the electrical conductivity and reflects the total content of dissolved ions in the water. The increase in the indicator after filtration indicates a decrease in the ionic concentration and confirms the effective removal of charged ions and a decrease in total mineralization, especially in *Stuckenia pectinata* (Barroso et al., 2023).

The proposed modular treatment system can be implemented as an additional stage of post-treatment after the storage and transportation of treated urban wastewater from the WWTP, immediately before its supply to irrigation systems. Thus, the device would perform the role of a "polishing step" to remove residual nutrients and microbial indicators, increasing the safety of reused water according to the requirements of Regulation (EU) 2020/741.

Although treated urban wastewater can meet the regulatory requirements for nitrogen and phosphorus content, its long-term use for irrigation poses a risk of accumulation of nutrients in the soil, leaching of nitrates into groundwater and increasing phosphorus content in the surface soil layers (Seymenov et al., 2025; Li et al., 2025; Saleh et al., 2025). Therefore, further reduction of concentrations through post-treatment of water is a key measure to prevent secondary pollution (Liu et al., 2025) and for the protection of water and soil resources (Ibrahim & Hammad, 2024)

Even in compliance with Regulation (EU) 2020/741, long-term irrigation with treated urban wastewater may lead to cumulative nitrogen (N) and phosphorus (P) inputs, since environmental risk is determined not only by nutrient concentration, but also by the total irrigation volume applied over time (Xie et al., 2024). At the same time, nutrient-rich reclaimed water may partially substitute mineral fertilizers and provide an additional source of nitrogen and phosphorus for agricultural crops. However, the effectiveness and environmental safety of such nutrient reuse strongly depend on crop type, nutrient demand, soil properties and irrigation management practices (dos Santos & van Haandel, 2021).

An initial TN concentration of approximately 10 mg/l and a seasonal irrigation rate of 500 m^3/da, about 5.0 kg N. da^{-1} year $^{-1}$ may be introduced into the soil annually at TP concentration of approximately 1 mg/l, phosphorus inputs may reach 0.5 kg P da^{-1} year $^{-1}$, resulting in cumulative loads of approximately 50 kg N. da^{-1} and 5 kg P da^{-1} over a 10- year period. Nutrient inputs from reclaimed or nutrient-enriched water can be comparable to those of conventional fertilization programs in intensive agriculture (López et al., 2025). In this context, reclaimed water may partially substitute mineral fertilizers, depending on crop type, growth stage, and nutrient demand—for example, leafy vegetables and fast-growing crops typically exhibit higher nitrogen uptake, whereas fruiting crops often require more balanced nutrient supply. However, when nutrient supply exceeds plant uptake capacity—particularly under conditions of high irrigation rates or in light-textured soils—there is an increased risk of nitrate leaching to groundwater (Chen et al., 2024). In addition, the accumulation of nitrogen and especially phosphorus in the topsoil can enhance the potential for surface runoff, nutrient losses, and subsequent eutrophication of receiving water bodies (Shen et al., 2025). Therefore, the agronomic benefits of nutrient reuse must be balanced against environmental risks through controlled nutrient management. International guidelines from the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) emphasize that safe water reuse practices should address not only microbiological quality but also salinity and nutrient loads (FAO & WHO, 2023). Nitrogen and phosphorus, are not included as mandatory parameters in the minimum quality requirements for reused water under Regulation (EU) 2020/741, however, their inclusion in risk management assessments is increasingly recognized as important for preventing long-term environmental impacts (Berbel et al., 2023).

6. Conclusion

- The experimental results demonstrate that both filtration configurations, incorporating natural zeolite (clinoptilolite) and biomass from *Stuckenia pectinata* followed by ultrafiltration, contributed to a significant reduction in the concentration of major nutrients (TN, N-NO_3, PO_4^{3-}- P) in the treated water after a 60-minute treatment cycle.
- In the zeolite-based system, removal efficiencies for total nitrogen (TN) and nitrate nitrogen (N-NO_3), reached 66.78% and 18.89% respectively. The filter containing *Stuckenia pectinata*, demonstrated comparatively higher efficiency, with TN removal

reaching 76.27% and phosphate removal (PO_4^{3-}- P) reaching 66.13% compared to 58.39% in the zeolite system. These findings highlight the potential of aquatic macrophyte biomass as a biogenic adsorptive material for nutrient reduction.

- The proposed pilot system provides a preliminary framework for integrated eco-technological nutrient mitigation in anthropogenically impacted surface waters. The synergistic use of mineral and biogenic adsorptive media demonstrated effective water quality improvement under controlled conditions.
- As a preliminary laboratory-scale study based on a single sampling event, the results should be considered indicative. Future investigations should include replicated experiments, sanitary-hygienic indicators and long-term assessment of system performance under environmental conditions in order to validate the observed trends and evaluate the practical applicability of the proposed system.

Conflict of Interest: The author declares no conflict of interest.

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