



Simultaneous Removal of Nutrients from Water Using Advanced Sustainable Technologies: A Comprehensive Systematic Review (2005-2024)

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ABSTRACT

Nitrates (NO_3^-) and phosphates (PO_4^{3-}) are released in high amounts of industrial waste and runoffs, causing the eutrophication process, which can impair aquatic life. The present paper is a systematic and comprehensive review of the most recent removal technologies, consisting of physical, chemical, biological, and nanotechnology technologies, and concentrates on newly published articles (since 2005). One of the studies deals with the complicated mechanisms of reaction, like ion exchange, electrostatic attraction, and the formation of a surface complex. The experiments showed that using a biochar-based adsorption system and nano-modified adsorbents is the most sustainable and economically applicable method, as the efficiencies of removal reach over 90% within the most favorable working environment. The review concludes that water treatment lies in the emergence of "Hybrid Systems" combining high efficiency with qualitative nutrient recovery in conformity with the concept of the circular economy and the resource-constrained areas.

1. Introduction

Water is a necessary ingredient of life on Earth and is generally thought of as a important resource for businesses moreover communities around the world. There are many places where you may find this kind of water, like rivers, lakes, ponds, as well as groundwater. It is very important for life and the ecosystem. But only around 1% of this freshwater is easy for people and businesses to get to. The rest is either unusable groundwater or glaciers that are hard to get to. Because of population expansion, industrialization, climate change, and the use of water to make energy, the lack of fresh water is becoming a major environmental issue (Chowdhary et al., 2020; Fida et al., 2023). Nitrates, on the one hand, are among the most

critical nutrients that facilitate biological growth; however, when concentrations exceed regulatory thresholds, they pose significant environmental and human health hazards. Overloading results in uncontrolled algal and cyanobacterial growth, which depletes oxygen, reduces biodiversity, and releases toxic compounds into water bodies. This has dire consequences on the application of water as a drinking source, irrigation, and industry (Karthikeyan et al., 2021; Onyango et al., 2010). The primary sources of contamination of nitrate and phosphate include industrial effluents, agricultural run-offs, and municipal wastewater. Production of fertilizers, mining, pharmaceutical manufacturing, metal finishing, and intensive agricultural practices impose significant loads of household fertilizers on

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surface and underground water systems to the excess of the standard rate that is accepted by the international community, including the World Health Organization, the Environmental Protection Agency (EPA), and the European Union (Rajmohan et al., 2016; Alagha et al., 2020a). Nitrate pollution in several aspects of the developing world has become one of the most common issues related to groundwater quality that can create severe risks to the entire community, which depends on untreated or under-treated water sources (Korostynska et al., 2012; Mahmud et al., 2020). Environmental influences and health effects of nitrate and phosphate contamination are established. In the human body, nitrate can be converted into nitrite, which in turn results in the development of carcinogenic N-nitrosamines and such conditions as methemoglobinemia in babies and phosphate-driven eutrophication that causes the collapse of ecosystems and the growth of toxin-producing microorganisms (Kumar et al., 2016; Kamimoto et al., 2019; Lazaratou et al., 2020). The impacts of this form of effect prove the urgency of effective and sustainable elimination strategies regarding nutrients. To reduce nutrient pollution, a full spectrum of technologies has been created, comprising chemical precipitation, membrane separation, biological denitrification, adsorption, and nanotechnology-based technologies (Xu et al., 2010; Bhatnagar and Sillanpää, 2011; Bartucca et al., 2016). Although traditional chemical and membrane cleaning processes can be very effective in the removal process, they have been linked to high energy usage, the use of chemicals, and the production of secondary wastes. A better alternative that is more eco-friendly is presented by biological processes, but they are sensitive to operating conditions and influent composition. Alternatively, significant future applications of nutrient capture can be found in adsorption and in new nanomaterial systems that use inexpensive or designed materials (Awual et al., 2011; Yin et al., 2018; Yang and Yao, 2018). In Iraq, the increased levels of nitrates and phosphates in the major river systems, including the Tigris, are strictly

connected with the agricultural runoff, untreated city wastewater, and industrial effluents. This fact predisposes the implementation of affordable and locally applicable treatment technologies to the national environmental management and water security policies (Alagha et al., 2020a; Korostynska et al., 2012). Thus, it is important to critically assess the technologies already shown to remove nutrients to find the solutions that are not only efficient but also economically as well as environmentally viable in actual real-life situations. In this review, a practical study of the most advanced chemical, biological, adsorption-based, and nanotechnology-based strategies in the removal of phosphates and nitrates in water and wastewater is conducted systematically. By comparing their operational limitations removal efficiency, costs, and sustainability aspects, this paper aims to provide a comprehensive framework for selecting suitable nutrient control strategies, particularly for application in developing and water-scarce regions. Nitrate fertilizers that plants in agricultural areas do not absorb will seep out of the soil and end up in freshwater, groundwater, and ocean water (Huang et al. 2017). Concentrations of phosphates and nitrates from various sources are shown in **Table 1**. After treating the 3.5 billion tons of dry biomass generated by the Baltic Sea coastal nations, a significant amount of wastewater with a 10–30% nutrient load is produced and released into the ocean (Zheng et al. 2017). Furthermore, research indicates that wastewater treatment plants (WWTPs) in the Netherlands account for 14% of the nitrogen load and 34% of the phosphorus load each year., that it is innovative, it is used in the section "Research Method" to describe the step of research and used in the section "Results and Discussion" to support the analysis of the results [3]. Furthermore, roughly 41% of nitrogen and 62% of phosphorus are produced by the agriculture sector (Hendriks and Langeveld 2017). High levels of phosphates and nitrates are released into water systems by industrial activities worldwide (Ashoori et al., 2019).

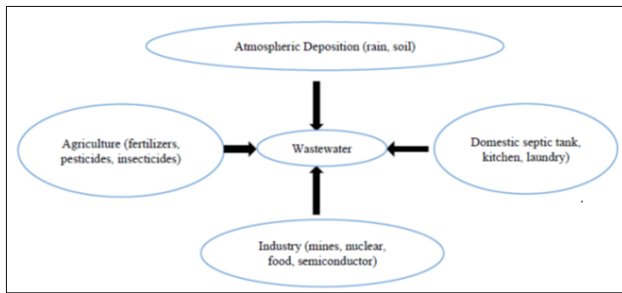


Figure 1 shows the four primary sources of wastewater: residences, businesses, agricultural land, and air deposition. The accumulation of nitrates and phosphates in aquatic environments is primarily attributed to these sources.

EUTROPHICATION

Among the worst effects of the overloading of nitrate and phosphates into water bodies is eutrophication. The release of these nutrients into rivers, lakes, and reservoirs via industrial effluents, agricultural runoff, and municipal wastewater causes rapid algae and cyanobacteria growth, which results in harmful algae blooms and the disruption of the ecosystem. These are blooms that hamper light penetration and disrupt aquatic food webs and eventually facilitate the depletion of oxygen caused by the breakdown of organic matter to create anoxic/hypoxic environments that pose risks to fish and invertebrate species (Akpor, 2011; Selvakumar and Sivashanmugam, 2017).

The phosphate has been well known as a limiting nutrient in most freshwater systems, that is, a slight increase in phosphate concentration can cause substantial eutrophication. The concentrations above 0.02 mg/L are optimal to favor the growth of algae, and the concentrations above 50 µg/L are linked to severe ecological degradation (Awwal et al., 2011; Yin et al., 2018). Phosphate exists as orthophosphate in the wastewater that is highly bioavailable and fixed readily by the microbes, further increasing nutrient-driven productivity (Korostynska et al., 2012; Bacelo et al., 2020). Nitrate is also an important factor in eutrophication, especially in flowing waters and surface systems that receive nitrogen through groundwater, where the nitrogen level governs the biological productivity. Nitrate is

readily carried away by runoff and adsorption onto soil characteristics, so agricultural and industrial sources of it can quickly diffuse to the receiving waters due to its great solubility and low attachment (Bhatnagar and Sillanpää, 2011; Kamimoto et al., 2019). High levels of nitrates increase the growth of phytoplankton, decrease dissolved oxygen, and assist in the synthesis of greenhouse gases like nitrous oxide in the process of the microbial transformation of both aquatic and sediment environments (He et al., 2018; Pastushok et al., 2019). In addition, ecological destruction and the stimulated eutrophication caused by nitrate and phosphate inputs have direct consequences for human health and water supply security. Cyanobacteria that generate toxins grow under favorable conditions, and because of their presence in drinking water, it pollutes it, raising the treatment expenses; furthermore, nitrate itself is a highly dangerous toxin as it forms nitrite and carcinogenic nitrosamines in the human body. When combined, the synergistic effect of the combination of nitrate and phosphate makes eutrophication much faster than either nutrient by itself. This brings up the need to establish treatment methods that achieve the dual goal of eliminating these two contaminants, not with a single approach, especially in areas where the development of agriculture and industry is great (Velusamy et al., 2021; Hafshejani et al., 2016).

CONTRIBUTIONS AND OBJECTIVES

The present review will attempt to design an in-depth and systematic evaluation of the advanced technologies in simultaneous elimination of nitrates and phosphates in water. The given paper makes its contribution in the field, with the objective of comparing chemical, biological, adsorption, and nano-methodologies with each other, considering the removal efficiency, operational expenses, and environmental friendliness. The other strong point is the special focus on the discussion of low-cost, renewable adsorbents, e.g., biochar, as a decentralized approach to wastewater

treatment. Moreover, the paper reveals the serious research gaps, as it is important to develop hybrid treatment systems and realize their practical implementation to the problem of nutrient pollution in regions with scarce resources.

To determine the latest methods of phosphates and nitrates elimination of water and wastewater, the study engaged in an extensive search of peer-reviewed scientific articles. The literature search conducted was conducted through two big scientific databases, Scopus and Web of Science, because of their extensive coverage of reputable journals in the research of environmental engineering and water treatment. The researches included in the research were restricted to the years 2005-2024 as it was found to be covering the old researches and the latest technological advancements of the area of nutrient removal strategies. The consideration was on publications that were in English only. Primary search terms include combinations of nitrate removal, phosphate removal, water treatment, wastewater treatment, adsorption, biological denitrification, chemical precipitation and nanotechnology. To be relevant and to improve the search result, the use of Boolean operators (AND, OR) took place. The inclusion criteria of the research studies used were: (i) peer-reviewed journal articles; (ii) articles that discussed the elimination of nutrients in water or wastewater; and (iii) studies that discussed the efficiency of their process, process, or problems in their operation. Papers on conferences, theses, and non-peer-reviewed reports, articles that lack quantitative data or a description of the procedures of removal were cut, as well. This review is an investigation paper in which the most relevant research was analyzed and critically discussed following the screening of titles, abstracts, and full texts.

REVIEW METHODOLOGY

This systematic review was executed in compliance with the PRISMA 2020 principles to guarantee transparency, reproducibility, and a methodical study selection approach. A thorough literature search was conducted utilizing the Scopus and Web of Science databases to find pertinent peer-reviewed

research published from January 2005 to December 2024. The search strategy was designed utilizing combinations of the following keywords: “nitrate removal,” “phosphate removal,” “simultaneous nutrient removal,” “wastewater treatment,” “adsorption,” “biological denitrification,” “chemical precipitation,” “nanotechnology,” and “hybrid systems.” Boolean operators like AND and OR were employed to enhance the search and increase the pertinence of the obtained entries.

The inclusion criteria encompassed peer-reviewed journal publications published in English that examined the removal of nitrate and/or phosphate from water or wastewater, detailing removal performance, processes, operational conditions, or sustainability considerations. Conference papers, theses, book chapters, non-English publications, and research deficient in adequate experimental or comparative data were removed.

A total of 1460 records were initially found from the chosen databases, comprising 820 entries from Scopus and 640 from Web of Science. Following the elimination of duplicate records, 1125 studies were retained for title and abstract screening. In the screening phase, 780 records were removed due to irrelevance or lack of focus on water or wastewater treatment. Subsequently, 345 full-text papers were evaluated for eligibility. Out of these, 207 articles were rejected for the following reasons: absence of quantitative data ($n = 102$), classification as conference papers or theses ($n = 64$), and publishing in a language other than English ($n = 41$). Ultimately, 138 research were incorporated into the qualitative synthesis, whereas 92 studies were chosen for comparative analysis.

Table 1: delineates the standard concentrations of nitrate and phosphate across various water sources and activities, accompanied with their environmental ramifications and cited references.

Activity / Water Source	Nitrate (NO ₃ ⁻) Range (mg/L)	Total Phosphate (TP) Range (mg/L)	Engineering & Environmental Context	Reference (APA)
Municipal Wastewater (Raw)	25 – 85	5 – 20	High nutrient load from detergents and human metabolic waste.	Al-Khafaji et al. (2021)
Agricultural Drainage	10 – 150	0.1 – 6.5	Highly variable; depends on fertilizer application and soil erosion.	Wang et al. (2022)
Chemical Fertilizer Industry	100 – 800	10 – 450	Concentrated streams requiring specialized pre-treatment (e.g., EBPR/Denitrification).	Nguyen et al. (2024)
Food & Dairy Processing	40 – 110	8 – 60	Often contains high organic nitrogen, which nitrifies during treatment.	Li et al. (2020)
Intensive Aquaculture	5 – 45	0.2 – 4	Accumulation from protein-rich feed and fish excretion.	Zhang et al. (2023)
Natural Pristine Waters	< 1	< 0.05	Values exceeding these levels indicate early-stage eutrophication.	Thompson et al. (2021)
WHO Drinking Standards	45 – 50	0.1 (Target)	Strict nitrate limits to prevent Methemoglobinemia in infants.	Ward et al. (2018)

The findings demonstrate that industrial and agricultural activities are the primary sources of nutrient pollution in contrast to natural water sources.

Systematic Review Methodology (PRISMA Flow Diagram)

The PRISMA framework was adopted to ensure transparency, reproducibility, and systematic selection of peer-reviewed studies.

REMOVAL OF NUTRIENTS PHOSPHATES IN WATER

Phosphates are vital minerals widely utilized in farming and numerous industrial processes. In wastewater, they are usually found in three main forms: orthophosphates, phosphates, pyrophosphates, metaphosphates, and polyphosphates, and organic phosphates (Korostynska et al, 2012; Yousefi et al, 2019; Barcelo et al, 2020). Of them, orthophosphate (PO₄³⁻) is the predominant form, making up around 50–70% of the total phosphate concentration. Additionally, several chemical species may be present, including phosphoric acid (H₃PO₄), hydrogen phosphate (HPO₄²⁻), dihydrogen phosphate (H₂PO₄⁻), and phosphate ions (Yin et al., 2018). Water quality gets worse and cannot be reused when phosphate levels go above permitted levels (Awual et al., 2011).

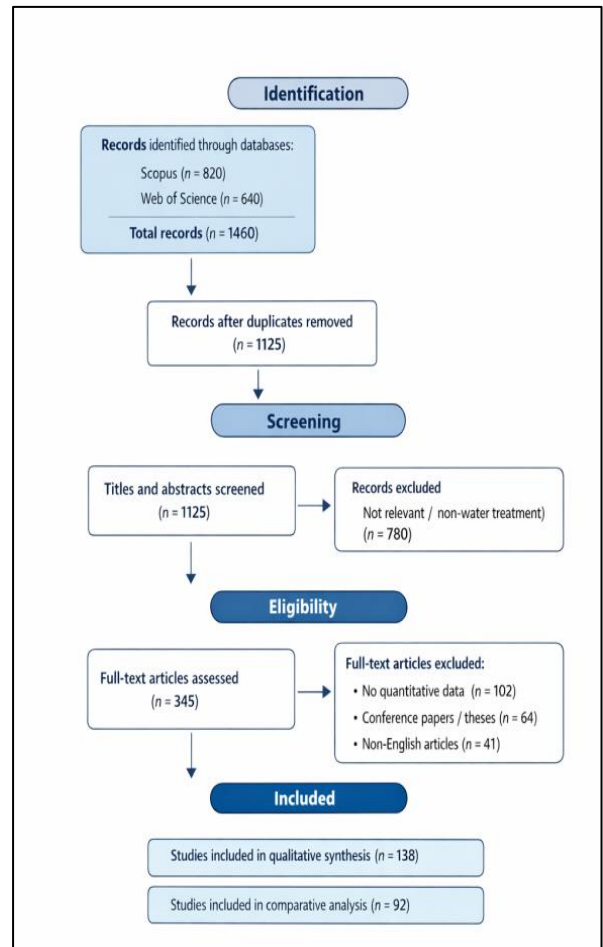


Figure 2. PRISMA Flow Diagram for Literature Selection Process (2005–2024)

High amounts of phosphates cause algae and other photosynthetic microorganisms to grow too much, which is called eutrophication. When this biomass breaks down, it uses up dissolved oxygen, which makes the water quality worse. Also, excessive levels of phosphate make water treatment more expensive and harder to do. Enhanced biological phosphorus removal (EBPR) is a frequent and successful way to cut down on the amount of phosphate that gets into water (Nassef, 2012; Korostynska et al., 2012; Wang et al., 2020). Moreover, excessive phosphate exposure may jeopardize human health and aquatic species, potentially leading to severe illnesses such as renal dysfunction and various metabolic disorders (Kumar et al., 2016).

NITRATES IN WATER

Nitrates are essential components in the manufacture of agricultural fertilizers and many industrial processes, and they are a major pollutant in wastewater. Nitrates exist in water in various chemical forms because of the nitrification of ammonia. The most stable and common form in aerobic aquatic environments is the nitrate ion (NO_3^-) (Al-Khafaji et al., 2021; Zhang et al., 2023). Water quality deteriorates and becomes unsuitable for reuse when nitrate concentrations exceed internationally accepted limits. High nitrate levels cause eutrophication, which stimulates excessive growth of algae and aquatic plants. When these algae decompose, they deplete dissolved oxygen (DO) furthermore degrade the aquatic environment (Wang et al., 2022). Moreover, high nitrate concentrations make water treatment processes more complex and costly. Bio-denitrification techniques and advanced aerobic-anaerobic processes are useful methods for reducing nitrogen loads before discharge (Li et al., 2020; Nguyen et al., 2024). From a health perspective, excessive nitrate levels lead to a serious risk to human health, being associated with methemoglobinemia (blue baby syndrome), thyroid problems, and certain cancers with prolonged exposure (Ward et al., 2018; Thompson et al., 2021). Environmentally, nitrate transformation processes contribute to the emission of nitrous oxide (N_2O), a potent greenhouse gas hundreds of times more

powerful than carbon dioxide, thus exacerbating global warming (He et al., 2018; Kamimoto et al., 2019). **Table 2** shows how the amount of nitrate varies in different types of industrial effluents. Nitrate may also come from natural processes in the nitrogen cycle in the air and the area around it (Pastushok et al., 2019).

COMPARISON OF REMOVAL TECHNIQUES

The reported removal efficiencies fluctuated considerably based on operating circumstances, including pH, temperature, contact time, initial nutrient content, wastewater composition, and the scale of the tests, whether laboratory-scale, pilot-scale, or real wastewater conditions. There are a lot of ways to treat wastewater that can get rid of nitrate and phosphate. Electrodialysis, ion exchange, and reverse osmosis are some of the most advanced methods used. Electrodialysis is very good in getting rid of nitrates. But these methods are generally linked to large operational expenses and technical difficulties, which may make them less useful in real life.

Therefore, there has been a thorough exploration of alternative and more cost-effective methods. These mostly include chemical treatment, biological systems, adsorption methods, and nanotechnology-based approaches, which have shown promising effectiveness in different environments (Rocca et al., 2007; Karthikeyan et al., 2019a). **Table 3** shows how various strategies compare to each other.

Table 2 Nitrate concentrations in industrial wastewater

Industry Type	Approximate Nitrate Concentration (mg/L)	Study Key Findings & Context	Reference
Chemical Fertilizer Industry	150 – 500	Extremely high concentrations require advanced biological denitrification processes.	Al-Khafaji et al. (2021)
Slaughterhouses & Food Processing	60 – 120	Resulting from the oxidation of organic nitrogen compounds during cleaning processes.	Wang et al. (2022)
Explosives & Mining Industry	200 – 1,000	Highly polluted water poses severe environmental risks if not chemically/biologically treated.	Nguyen et al. (2024)
Tannery Industry	30 – 90	Linked to high ammonia levels that convert to nitrates during aerobic treatment stages.	Li et al. (2020)
Electronics Manufacturing	50 – 250	Originates from the use of nitric acid (HNO ₃) in cleaning and etching operations.	Zhang et al. (2023)

Table 3: Summarizes the Principal Nutrient Removal Methodologies and the Frequently Utilized Materials Documented in The Literature.

Removal Methods	Materials used	References
Chemical methods	precipitation using metal salts such as iron, aluminum, calcium, magnesium and lime.	De-Bashan & Bashan (2004)
Biological methods	Microbial denitrification processes	Lee et al. (2009), Nakarmi et al., (2020)
Adsorption methods Nanotechnology	Biochar-based adsorption Application of nanoparticles including, Nanoscale zero-valent iron (NZVI), cobalt nanoparticles, nickel, carbon/titanium oxide nanoparticles, iron/palladium nanoparticles, nanotubes like carbon nanotubes, nanofibers like chitosan nanofibers, nanoclusters like spherical nanoscale zero-valent iron, and nanocomposites like carbon-silicon, chitosan/polyethylene glycol (PEG), zeolite/chitosan/chitosan/polystyrene zinc, nano zirconium oxide/ lanthanum-doped magnetic graphene sheet.	Yin et al. (2018) Yang & Yao (2018), Xiaoqiang et al. (2019)

CHEMICAL METHODS

Chemicals such as iron, aluminum, calcium, magnesium and lime, which are made of metals, are commonly used by people to extract phosphorus in wastewater (de-Bashan and Bashan, 2004). Dissolved phosphate ions are used in this process in reactions with other chemicals to form molecules that are not dissolvable and can be separated as precipitates. The reactions typically create big, floc-like particles that make it easier to remove (Ruzhitskaya and Gogina, 2017; Jutidamrongphan et al., 2012). Divalent and trivalent metal salts can be used to reduce phosphates and nitrates. But this plan is more effective in disposing of phosphate. Compounds based on aluminum, in particular aluminum hydroxide, are effective since they can adsorb a significant amount of various forms of phosphate, and can do so effectively when the pH is varied. Iron and aluminum oxides can also be used in long-term adsorption, as well as activated alumina is the best in removing low phosphate levels (around 1 mg/L) (Kumar and Viswanathan, 2020; Manikam et al., 2019; Belkada et al., 2018). Adding magnesium salts to anaerobic digestion systems can help get rid of phosphorus and make the treatment work better by lowering the number of suspended particles and chemical oxygen demand while increasing the amount of biogas produced. In basic conditions (around pH 10.5), higher removal rates for ammonia and phosphorus can be reached at the same time. (Carvalho et al. 2007; Okano et al. 2015; Chakraborty et al. 2017). Calcium-based dropping is an easy and low-cost way for taking out phosphate by making calcium phosphate mixes like hydroxyapatite. This method works best when the pH is from 8.0 to 8.5, and it can take away around 75–85% of the stuff without much trouble from making calcium carbonate (de-Bashan and Bashan 2004; El-Nahas et al. 2019). Zero-valent iron has also been looked at for nitrate drop, but its use is limited due to troubles such as ammonium form and the need for tight pH control Bhatnagar and Sillanpää, 2011; Wu et al., 2016. Even if chemically fixed steps are very good, there are still some issues. These include making a lot of chemical mud, needing

to do something with the byproducts after fixing, and being sensitive to changes in temperature and pH. Chemical ways can usually take away more than 60–70% of dirt, even if they might not work best for wastewater that is high on nitrates Bhatnagar and Sillanpää 2011 Kumar et al, 2019a, b). The biggest engineering obstacle to chemical methods lies not in their removal efficiency (75–85%), but in managing the resulting chemical sludge. Recent studies indicate that chemical phosphate precipitation increases sludge volume by 25–40% compared to biological treatment, thus raising transportation and final disposal costs (Zheng et al., 2017). From an engineering perspective, this sludge requires complex thickening and drying processes due to its high-water content and the difficulty of dewatering it, as well as the risk of the associated heavy metals redistributing into the soil if it is not disposed of in engineered landfills (Khan et al., 2024).

BIOLOGICAL METHODS

Living treatment is a usual way to remove nitrates, mostly by tiny life forms changing nitrates into nitrogen gas when oxygen isn't needed. Small creatures change nitrate into nitrogen gas in this process, which doesn't need oxygen. Denitrification can be categorized into heterotrophic and autotrophic routes, depending on the type of carbon source employed. Heterotrophic denitrifiers employ organic substances, like methanol, ethanol, acetate, or other carbohydrates, as carbon sources for growth and as electron donors for nitrate reduction. This technique is applicable to both conventional and recirculating wastewater treatment systems, demonstrating high nitrate removal efficiency under optimal operating conditions, including suitable carbon-to-nitrogen ratios, pH levels, and dissolved oxygen concentrations (Bhatnagar & Sillanpää, 2011; Yang et al., 2017; Rajesh Banu et al., 2020).

Its performance, on the other hand, is very sensitive on operational parameters such as the carbon-to-nitrogen ratio, temperature, pH, and dissolved oxygen levels, which can have a big effect on process stability (Lee et al., 2009; Jena et al., 2016).

On the other hand, autotrophic denitrification uses inorganic carbon sources like bicarbonate or

carbon dioxide; there is no need for outside organic inputs. This method cuts down on the formation of too much biomass and sludge, but it usually has slower reaction rates and needs bigger reactor contents to get the same level of removal efficiency (Ghafari et al., 2008). Biological denitrification efficiency usually falls between 60% and 95%, depending on how the system is set up and how it is used. Optimal circumstances contribute to better performance (Lee et al., 2009; Salehi & Hosseini-fard, 2020). Fig. 3) shows the primary metabolic processes that are involved in changing nitrates during denitrification. Biological systems can also help get rid of phosphorus through enhanced biological phosphorus removal (EBPR). Standard EBPR processes usually only remove a moderate amount of phosphorus. This can be improved by increasing the concentration of the sludge or the amount of time it stays in the system, but this often means more sludge is made and it is harder to handle (Mohammadi et al., 2019; Zhang et al., 2018a, b). Numerous biological nutrient removal systems can concurrently eliminate nitrogen and phosphorus, including Extended Anaerobic Sludge Contact (EASC), University of Cape Town (UCT), Anaerobic–Oxic (A/O), and Phoredox processes. The UCT system has demonstrated significant efficacy in concurrent nutrient removal under regulated working circumstances (Ruzhitskaya and Gogina, 2017). Furthermore, photosynthetic microorganisms, including microalgae, have been examined as alternative biological treatment solutions owing to their nutrient absorbing capabilities. *Chlorella vulgaris*, *Scenedesmus dimorphus*, and *Spirulina platensis* have shown that they can get rid of nitrate, phosphate, and ammonium species in regulated settings (de-Bashan and Bashan, 2004; Pan et al., 2020). Even with these benefits, biological treatment methods are still affected by things like changes in temperature and microbial activity. Also, with low-carbon wastewater, the demand for outside carbon sources can make both the economy and the environment less stable. So, Biological techniques are effective at eliminating nitrates, but they are less effective at eliminating phosphates than chemical and

adsorption-based techniques (Bhatnagar and Sillanpää, 2011; Breida et al., 2018).

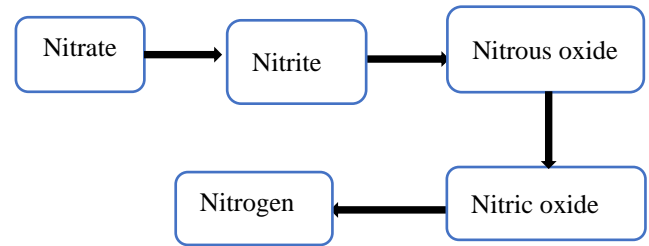


Figure 3: In the nitrogen cycle, denitrification includes the stepwise reduction of nitrate to nitrogen gas through intermediate compounds such as nitrite, nitric oxide, with environmental microorganisms playing important role in driving these processes

Activated sludge-based biological treatment effectively removes phosphorus, with conventional systems generally achieving 20–40% removal. Advanced configurations, such as Anaerobic-Oxic (A/O), Extended Anaerobic Sludge Contact (EASC), Bardenpho, Phoredox, and University of Cape Town (UCT) systems, can significantly enhance the simultaneous removal efficiency of nitrogen and phosphorus (Mohammadi et al., 2019; Zhang et al., 2018a, b; Delgadillo-Mirquez et al., 2016; Ruzhitskaya & Gogina, 2017).

Heterotrophic species, including cyanobacteria and microalgae, have demonstrated significant efficacy in nutrient removal. Species such as *Scenedesmus dimorphus*, *Chlorella vulgaris*, and *Spirulina platensis* have exhibited the capacity to eliminate phosphate, nitrate, and ammonia from diverse wastewater types (de-Bashan and Bashan, 2004; Pan et al., 2020). Although biological systems exhibit great efficiency and moderate operational costs, they are susceptible to temperature variations, carbon availability, and operational circumstances, necessitating effective biomass management and post-treatment (Bhatnagar & Sillanpää, 2011; Breida et al., 2018). Moreover, autotrophic systems are often hampered by slow reaction kinetics and operational instability, whereas heterotrophic denitrification in low-carbon wastewater remains dependent on the costly addition of external carbon sources.

ADSORPTION

Because of its ease of use, flexibility in design, and simplicity of operation, adsorption is considered a top method for treating wastewater. By utilizing solute interactions with the adsorbent's surface, this method effectively removes inorganic anions such as fluoride, nitrate, perchlorate, and bromate (Ji et al., 2020; Zheng et al., 2020). However, the physicochemical characteristics of the adsorbent, such as its pore structure and functional groups, strictly determine the system's overall performance. Because of their high surface area and chemical stability, carbon-based materials like powdered activated carbon (PAC) and carbon nanotubes (CNTs) are still widely used, but their large-scale application is frequently hampered by high costs and regeneration issues, especially in developing regions (Li et al., 2020a, b) (Rezvani et al., 2019). Beyond carbon, clay-based minerals and industrial byproducts like fly ash and red mud offer cheaper alternatives for nitrate removal via ion exchange, though they face limitations regarding lower adsorption capacities and the risk of secondary pollutant leaching (Bhatnagar and Sillanpää 2011) (Jaafari et al., 2019). Similarly, the valorization of agricultural residues such as rice hulls, wheat straw, and coconut shells into anion exchangers has gained traction as an eco-friendly approach, with some materials even outperforming commercial charcoal at low temperatures (Shen et al., 2019; Lalley et al., 2016). Currently, modified biochar, including magnetic and Mg-Al variants, represents one of the most promising avenues for the concurrent removal of phosphates and nitrates through enhanced surface complexation (Yin et al. 2018; de Vargas Brião et al. 2020). Nevertheless, the long-term sustainability of these systems depends heavily on addressing surface saturation, the influence of pH, and the efficiency of regeneration protocols (Hafshejani et al., 2016; Mohan et al., 2014). Their enormous effectiveness, the complexity of regeneration, as well as the potential resulting secondary contamination of the surface through the leaching effects of surface modifiers, remain major impediments to the popularization of adsorption systems. In situations where biochar

and agricultural wastes are used as inexpensive materials, adsorption technologies have a promising cost efficiency relationship. Nevertheless, the main limitations to adsorption are the manipulation of the used adsorbent. Secondary pollution through improper loading of phosphate and nitrate during disposal or poor regeneration of the same can be a disadvantage of the entire environmental benefit of the process.

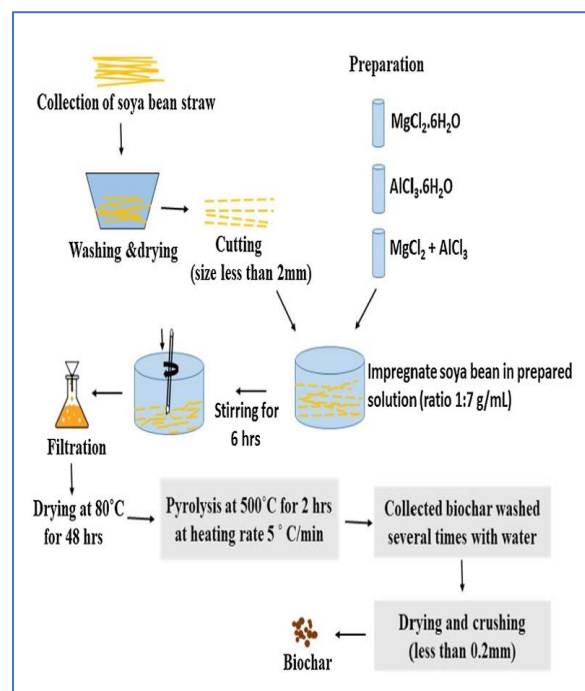


Figure 4 shows the steps that need to be completed to make charcoal from soybeans. It involves gathering the raw material, cleaning it, and after being reduced to small pieces, the material is immersed in a prepared solution, followed by filtering, drying, and pyrolysis to obtain biochar (Velusamy et al., 2021).

Because it is easily produced locally using basic pyrolysis units based on easily accessible agricultural waste, biochar stands out as a superior engineering alternative, especially in underdeveloped places (Ahmad et al., 2024). The material's elevated porosity and surface functional groups facilitate phosphate and nitrate removal efficiency surpassing 90% under optimum laboratory circumstances, contingent upon pH, contact duration, and wastewater parameters. Nonetheless, regeneration costs must be taken into account, while alkaline or saline regeneration can prolong its lifespan for up to five cycles and diminish operating expenses

relative to commercial activated carbon (Zhu & Chen, 2024).

NANOTECHNOLOGY

Because of the special physicochemical properties of nanoparticles, nanotechnology has become a cutting-edge method for the effective extraction of nitrates and phosphates from aqueous environments. Carbon-based nanomaterials, nickel and cobalt nanoparticles, and other nanocomposites are examples of these materials, which usually have sizes between 1 and 100 nm (Sithara et al., 2017; Yang & Yao, 2018), (Xiaoqiang et al., 2019). These materials' large specific surface area, increased chemical reactivity, and strong adsorption-reduction capabilities are the main reasons for their remarkable removal performance. Among these, nanoscale zero-valent iron (nZVI) has attracted a lot of interest; its superior reducing capacity and catalytic activity make it particularly effective for the simultaneous remediation of nitrate and phosphate contaminants (Hobbie et al., 2017), (Salipira et al., 2007). Nevertheless, environmental conditions, in particular, pH considerably affect the performance of nZVI. Even though high removal efficiencies have been achieved in an acidic condition, surface oxidation and particle aggregation have led to a sharp decline in removal efficiency at a close to neutral pH (Tyagi et al. 2018). Such limitations put in question the ability of nZVI to withstand and be effectively employed in real circumstances of water treatment. Examples of supported and modified nanomaterials that have been synthesized to overcome the issue of aggregation and stability include zeolite-based Fe/Ni bimetallic nanoparticles and as well as nano-Fe (OH)₃/clinoptilolite (He et al. 2018; Madhura et al. 2019; Marcelo et al. 2020). Due to the synergistic incorporation between the nanoparticle and the surrounding matrix, these materials are more dispersible and enhanced in removal. Yet, the high complexity of synthesis procedures and the necessity to have complete control over the composition of materials can restrict their generalizability on a large scale. Silica nanoparticles prepared out of rice husk ash and graphene-based nanocomposites have also been considered to remove nitrate and

phosphate; in rational conditions, the absorptive abilities have proved to be promising (Kumar et al. 2019a, b). Although these encouraging results have been obtained, operation considerations for instance adsorbent dosage, pH, contact time, and the competing ions still play a significant role in adsorption performance. Secondly, the release of nanoparticles, toxicity, and aquatic accumulation have dire impacts on the environment, which are important environmental issues that should be put into proper consideration. Comprehensively, although nanotechnology-based techniques show amazingly good nutrient removal capabilities, it is arguably the prohibitively high cost of synthesis, stability issues, potentially detrimental effects on the environment, and the difficulty of scaling the results in the laboratory to industrial scale that restrain their practical implementation. Thus, the utilization of nanomaterials in the water and wastewater treatment systems cannot be broadened before further studies can improve their environmental friendliness, reuse capacity and cost-effectiveness. The removal mechanisms involve surface redox reactions as well as electrostatic interactions but at neutral pH, nanoparticles aggregation and instability significantly reduce usefulness. Nanotechnology-based technologies have significant efficacy in controlled laboratory environments; however, elevated production costs, particle agglomeration, and potential ecotoxicological hazards restrict their large-scale implementation. Moreover, the environmental stability and the environmental fate of the nanoparticles remain unclear in the long run and thus acceptance in the society and regulatory approval cannot be easily attained. Adsorption based systems which utilize low-cost renewable materials have become the most viable choice of a decentralized and sustainable way of removing nutrients and hybrid systems with biological and adsorption processes are a promising future development (Zhu and Chen, 2024). Notwithstanding the encouraging removal efficacy of nanoparticles like nZVI in expedited nutrient elimination under laboratory settings, their extensive deployment in actual treatment facilities encounters several obstacles, including potential toxicity and issues in separation. Recent evaluations suggest that nanoparticles

may migrate into treated water, resulting in detrimental impacts on aquatic microbes (Zheng et al., 2017). From an engineering perspective, the recovery process for these particles after treatment presents a technical burden requiring expensive magnetic separation units or microfiltration membranes, thus reducing their economic appeal compared to more practical solutions such as hybrid systems (Khan et al., 2024; Zhu & Chen, 2024). Simultaneous nitrification-denitrification (SND) and nutrient biosorption are the most prevalent routes. The insight into these different mechanisms is required to develop selective adsorbents having the ability to effectively target both categories of nutrients in multi-ionic wastewater matrices (Akinawo, 2023). **Table 4** illustrates that adsorption-based technologies provide an advantageous equilibrium between removal efficiency and economic viability, whereas membrane and nanotechnology-based systems get superior efficiencies under more regulated and expensive operational settings.

MECHANISTIC INSIGHTS INTO NUTRIENT REMOVAL

Displacement of nitrates (NO_3^-) and phosphates (PO_4^{3-}) in purified water is a complicated response to modes of physics and chemical factors. Based on the literature, as indicated in **Table 5**, the main process of the removal of both ions is the electrostatic attraction, particularly at the condition that the adsorbent surface is positively charged (P ZC - pH). Phosphates, however, tend to have higher removal capacity because they are able to result in internal surface complex and the bond exchange, where phosphate oxygen atom establishes a strong covalent bond with the metal hydroxyl group on the adsorbent surface. By contrast, ion exchange or external complexes are the main mechanism of inactivating the nitrate and, consequently, it is easier to compete with other anions, including sulfates and chlorides. In the case of bio-adsorbents and modified clays, the presence of functional groups like amino ($-\text{NH}_2$) also hydroxyl ($-\text{OH}$) helps in the formation of hydrogen bonds and filling of pores. Moreover, in the hybrid as well as biological systems; The

comparison shows that biochar techniques are the most cost-effective, with treatment costs not exceeding \$0.15 per cubic meter, due to the potential use of local agricultural waste as a feedstock (Ahmad et al., 2024). In contrast, the cost of chemical methods increases significantly when sludge treatment and drying costs are added, potentially adding up to \$0.20/m³ to the base cost (Khan et al., 2024). From a practical standpoint, investing in hybrid systems, despite their higher capital costs, offers long-term economic savings through nutrient recovery. Converting recovered phosphates into commercial products (such as struvite) can offset 15–20% of the plant's operating costs, thus reinforcing the concept of a circular economy in environmental engineering (Wang et al., 2024). **Table 6** provides a comparative economic study of several nutrient removal strategies, focusing on expected costs, material sources, and economic sustainability.

Table 4 Offers A Comparative Assessment of The Primary Nutrient Removal Systems Including Efficiency, Operational Parameters, Cost, Constraints, And Appropriate Applications.

Technique	Main materials	Removal efficiency	Operating conditions	Cost	Operational limitations	Suitable application
Chemical method. (precipitation, coagulation, ion exchange)	Iron, aluminum, lime, calcium, magnesium salts	Phosphate: 75–95% Nitrate: 40–70%	pH 6–10; chemical dosing; ambient temperature	High	Chemical sludge production, pH sensitivity, excessive chemical use, and secondary pollution	Industrial wastewater and drinking water under controlled conditions
Biological methods (denitrification, EBPR)	Heterotrophic and autotrophic bacteria, activated sludge	Phosphorus is moderate (20–50%), and nitrate is high (60–95%).	pH 6.5–8.5; T = 15–35 °C; anoxic/oxic zones; carbon source required	Medium	sensitive to pH, temperature, carbon availability, the need for biomass management, and the necessity of post-treatment	Municipal and industrial wastewater
Adsorption (activated carbon, biochar, agricultural wastes)	Biochar, modified biomass, activated carbon, zeolite	Nitrate: 40–90% Phosphate: 50–95%	pH 4–8; ambient temperature; contact time dependent	Low to medium	Adsorbent saturation, difficulties with regeneration, and possible leaching-related secondary pollution	Low-cost, decentralized systems for agricultural wastewater
Nanotechnology-based methods (nZVI, nanocomposites, graphene-based materials)	nZVI, nanocomposites, graphene-based materials	Nitrate & phosphate: 80–99%	pH sensitive (often acidic); controlled conditions	High	High synthesis costs, stability problems, possible toxicity, aggregation of nanoparticles, and restricted scalability	Point-of-use systems and specialized industrial wastewater
Membrane processes (RO, NF)	Reverse osmosis, nanofiltration, and electro dialysis	Nitrate & phosphate: >95%	High-pressure, high-energy input	Very high	concentration disposal, excessive energy consumption, and membrane fouling	Advanced industrial treatment and drinking water

Table 5: Dominant Removal Mechanisms for Nitrates and Phosphates (Adapted from Akinawo, 2023)

Treatment Method	Dominant Mechanism	Target Nutrient	Strength of Interaction
Adsorption (Biochar/Clays)	Electrostatic Attraction and Ion Exchange	NO ₃ ⁻ , PO ₄ ³⁻	Physical / Moderate
Modified Adsorbents (Metal Oxides)	Surface Complexation and Ligand Exchange	PO ₄ ³⁻	Chemical / Strong
Ion Exchange Resins	Stoichiometric Anion Exchange	NO ₃ ⁻ , PO ₄ ³⁻	Chemical / High
Biological Treatment	Denitrification & Polyphosphate	NO ₃ ⁻ , PO ₄ ³⁻	Metabolic / Variable

Chemical Precipitation	Accumulation Formation of Insoluble Salts (e.g., Struvite)	NO_3^- , PO_4^{3-}	Chemical / Irreversible
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Table 6 Comparison of Operating Costs and Economic Feasibility of Different Treatment Technologies

Treatment Technology	Estimated Cost (USD/m ³)	Key Cost Drivers	Economic Feasibility & Application	Key References
Chemical Precipitation	0.35 – 0.65	Chemical dosage (alum/ferric) and intensive sludge management.	High CAPEX/OPEX; suitable for large-scale centralized plants.	(Khan et al., 2024; Zheng et al., 2017)
Bio-adsorption (Biochar)	0.05 – 0.18	Feedstock collection, pyrolysis process, and chemical regeneration.	Highly feasible for decentralized and rural areas; aligns with Circular Economy.	(Ahmad et al., 2024; Zhu & Chen, 2024)
Advanced Biological (MBR/SBR)	0.45 – 0.80	High energy consumption for aeration and membrane fouling control.	Effective for high-quality effluent requirements and water reuse.	(Zhang et al., 2023)
Nanotechnology (nZVI/Composites)	0.95 – 1.60	High synthesis costs and complex magnetic/membrane separation.	Limited to specialized industrial applications due to high operational costs.	(Zhu & Chen, 2024; Zhang et al., 2016)
Hybrid Systems	0.25 – 0.55	Integrated maintenance of biological units and adsorbent replacement.	Balanced cost-efficiency; optimal for simultaneous removal and nutrient recovery.	(Khan et al., 2024; Ahmad et al., 2024)

Table 7 Comparative Economic Analysis of Different Nutrient Removal Technologies

Economic Sustainability	Material Source	Estimated Cost (USD/m ³)	Technology
Low (Sludge disposal costs)	Synthetic Chemicals	Medium to High	Chemical Precipitation
Medium (Regeneration costs)	Synthetic Resins	High	Ion Exchange
High (Long-term operation)	Microorganisms	Low to Medium	Biological Removal
Low (High material price)	Activated Carbon	High	Commercial Adsorbents
Very High (Circular Economy)	Agricultural Waste	Very Low	Green Adsorbents (Biochar)
Low (Energy intensive)	Advanced Polymers	Very High	Membrane Filtration

Table 7 illustrates that green adsorbent, such as biochar, provides superior economic sustainability owing to their low cost and local availability, whereas membrane filtration and ion exchange are less economically viable due to elevated operational and maintenance expenses.

SUSTAINABILITY, CIRCULAR ECONOMY, AND REUSE IN NUTRIENT REMOVAL TECHNOLOGIES

Adopting sustainability and circular economy concepts is a modern trend in wastewater treatment technology development. Treatment processes are no longer limited to pollutant removal but now aim to recover and reuse resources within integrated ecosystems. In the context of nutrient removal, nitrogen and phosphorus compounds are viewed as valuable recoverable resources rather than pollutants to be disposed of, promoting the shift towards

resource recovery-based treatment systems (Wang et al., 2024). Among the most well-known uses of the circular economy in water treatment are adsorbents made from biomass, especially biochar made from agricultural waste. They make it possible to repurpose low-value organic waste and turn it into extremely effective functional materials for nutrient removal. In addition to minimizing operational costs when compared to industrial materials, this method helps reduce solid waste generation and the carbon footprint associated with creating traditional adsorbents (Ahmad et al., 2024). According to recent research, biochar that has

been chemically or nano-modified has better surface characteristics and more efficient adsorption sites, which improves the removal of phosphate and nitrate from water. But once the adsorption process is over, these materials' actual value within a circular economy framework becomes apparent. Then, nutrient-rich materials can be recycled directly into agricultural systems as slow-release fertilizers or soil conditioners (Zin et al., 2024). Additionally, recent evaluations show that evaluating the sustainability of adsorbent materials requires integrating adsorption methods with the ideas of regeneration and reusability. Repeated cycles of use improve treatment systems' long-term economic viability by lowering resource and energy consumption (Khan et al., 2024). An essential method for assessing the overall environmental impact of changed materials, especially when employing nanomaterials or chemically treated materials, is environmental lifecycle assessment. Because of this, the development of future nutrient removal technologies necessitates a change from a paradigm of removal efficiency alone to one of sustainable efficiency that incorporates high performance, reusability, and less environmental effect. Thus, including circular economy principles into the design of adsorbent materials is a viable way to achieve more sustainable water treatment systems, especially in places where water resources are few and low-cost, high-efficiency solutions are required.

3. ANALYTICAL DISCUSSION

1. Suitability of Technologies to Iraq and Regional Conditions (Heat and Water Scarcity)

The success of simultaneous removal technologies in the Middle East, and Iraq specifically, cannot be assessed without considering extreme climatic conditions. High temperatures (exceeding 45°C in summer) directly affect the efficiency of biological systems; they increase the rate of biochemical reactions but can also lead to a decline in biomass stability and a decrease in dissolved oxygen (Zheng et al., 2017). From an

engineering perspective, biosorption (Biochar) emerges as an ideal solution for these conditions, as it possesses high thermal stability and is not affected by climatic fluctuations like sensitive biological systems (Ahmad et al., 2024). Furthermore, given the water scarcity crisis facing Iraq, technologies that allow to produce high-quality treated water suitable for agricultural reuse become a strategic necessity, not a secondary option (Khan et al., 2024).

2. Upscaling Challenges

Despite the promise shown by hybrid systems in laboratory studies, their transition to full-scale industrial applications faces significant engineering hurdles that explain their limited widespread adoption to date:

- **Biomass Stability:** In hybrid systems that combine biofilms and adsorbents, maintaining a balance of microorganisms presents a major challenge. Adsorbents or nanoparticles can inhibit the activity of denitrifying bacteria (Zhang et al., 2023).
- **Filter Clogging and Fouling:** Clogging is the primary technical obstacle. In real-world treatment plants, suspended solids and dense biological growth can clog the pores of adsorbents or membranes, requiring frequent backwashing, which increases energy and maintenance costs (Zhu & Chen, 2024).
- **Operational Complexity:** Hybrid systems require highly skilled engineering personnel to manage the overlapping parameters, which may be lacking in decentralized facilities or developing regions (Khan et al., 2024).

3. From Removal to Resource Recovery: The fundamental shift presented in this discussion is the need to view recovered phosphate as an economic asset. Using saturated adsorbents as slow-release fertilizers offers a dual solution: water treatment and supporting food security in areas suffering from soil degradation (Wang et al., 2024). This approach aligns perfectly with the vision of a circular economy and reduces

reliance on imported chemical fertilizers (Ahmad et al., 2024).

4. RECOMMENDATIONS

Based on the above, the following are recommended for publication and practical application:

- **Development of Hybrid Systems:** Focus on integrating adsorption technologies with biological treatment to ensure stable performance under varying operating conditions.
- **Practical Application:** Further studies should be conducted on "real wastewater" rather than laboratory solutions to understand the impact of interfering ions and organic matter.
- **Life Cycle Assessment (LCA):** Future research should include a comprehensive environmental and economic assessment of nano-modified adsorbents to ensure they do not cause secondary pollution.
- **Improving recovery techniques:** Developing effective protocols for regenerating adsorbents or directly converting them into agricultural fertilizers to support system sustainability.

5. CONCLUSION

This thorough review critically evaluates advanced methods for the concurrent removal of nitrate and phosphate from water and wastewater, encompassing chemical, biological, adsorption-based, membrane, and nanotechnology-driven systems. The investigation indicated that no singular treatment strategy can attain optimal performance across all operational settings. Adsorption technologies, especially those employing biochar and materials derived from agricultural waste, were recognized as the most sustainable and economically viable choice for decentralized and cost-effective applications, with removal efficiencies often surpassing 80–90% under optimized laboratory conditions.

Biological systems exhibit significant efficacy in nitrate removal; however, their performance is markedly sensitive to temperature, pH, carbon

availability, and influent composition. Membrane and nanotechnology-based systems attained remarkable nutrient removal rates, frequently above 95%; however, their practical application is constrained by elevated operational costs, energy requirements, and possible environmental issues.

Hybrid systems that combine adsorption and biological treatment seem to be the most promising future approach for attaining high removal efficiency, operational stability, and nutrient recovery within a circular economy framework. Future research must concentrate on comprehensive applications, authentic wastewater conditions, adsorbent regeneration, and life cycle assessment to guarantee enduring environmental and economic sustainability.

6. FUTURE PERSPECTIVES

In future studies, the development of hybrid operations that are a combination of adsorption with other treatment processes is needed to achieve the highest removal efficiency and minimize the operational limitations. The knowledge of removal techniques under real water conditions, that is, when different ions and organic matter are present, needs attention. Such techniques as lifecycle assessment, regeneration methods, and environmental risk assessment must be incorporated in future research methodologically, especially in cases of nanomaterials and altered adsorbents. Decentralized and not limited mass nutrient removal procedures in these desperate, developing, and water-deprived ends will necessitate the development of low-cost, proximate, and ecologically minimal materials.

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