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Review of emerging technologies for nutrient removal in wastewater treatment

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Abstract

The burgeoning global population and industrial activities have significantly increased the generation of wastewater laden with nutrients, posing severe environmental and public health concerns. Traditional wastewater treatment methods often fall short in effectively removing nutrients like nitrogen and phosphorus, leading to eutrophication of water bodies and endangering aquatic ecosystems. In response, emerging technologies for nutrient removal in wastewater treatment have gained traction in recent years, offering innovative and efficient solutions to mitigate nutrient pollution. This comprehensive review explores the latest advancements in nutrient removal technologies, encompassing biological, physical, and chemical processes. Biological treatment methods, including activated sludge, sequencing batch reactors (SBRs), and membrane bioreactors (MBRs), have been extensively studied and optimized for nutrient removal. Novel biofilm-based systems, such as moving bed biofilm reactors (MBBRs) and integrated fixed-film activated sludge (IFAS), have demonstrated enhanced nutrient removal capabilities and resilience to fluctuations in wastewater composition. Furthermore, the integration of advanced oxidation processes (AOPs) and membrane technologies has revolutionized nutrient removal from wastewater. AOPs, such as ozonation, ultraviolet (UV) irradiation, and photocatalysis, offer effective means to degrade recalcitrant organic pollutants and disrupt nutrient cycles. Membrane-based technologies, including reverse osmosis (RO), nanofiltration (NF), and forward osmosis (FO), enable selective nutrient removal and concentration, thereby producing high-quality effluent suitable for reuse or discharge into sensitive environments. Additionally, the review delves into emerging chemical treatment strategies, such as adsorption, precipitation, and ion exchange, for targeted removal of nutrients from wastewater streams. Advanced adsorbents and nanomaterials exhibit superior adsorption capacities and selectivity for nitrogen and phosphorus compounds, paving the way for cost-effective nutrient recovery and resource recycling. Moreover, the review highlights the importance of process optimization, system integration, and environmental sustainability in the development and deployment of emerging nutrient removal technologies. Life cycle assessments (LCAs) and techno-economic analyses provide valuable insights into the environmental footprint and economic viability of these innovative solutions, guiding decision-makers towards sustainable wastewater management practices. In conclusion, the synthesis of biological, physical, and chemical processes in emerging nutrient removal technologies holds great promise for addressing the challenges of nutrient pollution in wastewater treatment. Future research directions should focus on scalability, energy efficiency, and holistic approaches towards achieving water quality goals and fostering a circular economy.

Keywords: Nutrient removal; Wastewater treatment; Emerging technologies; Biological processes

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1. Introduction

Nutrient pollution in wastewater has become a pressing environmental concern worldwide due to its detrimental effects on water quality and ecosystem health. The discharge of excessive nitrogen and phosphorus compounds from various sources, including municipal, industrial, and agricultural activities, has led to widespread eutrophication of water bodies, harmful algal blooms, and degradation of aquatic habitats. Addressing this challenge necessitates the development and implementation of effective nutrient removal technologies within wastewater treatment systems (Bashir, et. al., 2020, Kesari, et. al., 2021, Saravanan, et. al., 2021).

Effective nutrient removal in wastewater treatment is crucial for several reasons. Firstly, excessive nutrients in effluent can cause imbalances in aquatic ecosystems, leading to the depletion of oxygen levels and the loss of biodiversity. Secondly, nutrient pollution poses risks to human health, as contaminated water sources can harbor pathogens and toxins associated with algal blooms. Additionally, nutrient-enriched effluent discharged into receiving waters can impair recreational activities and compromise the aesthetic value of natural environments. Therefore, ensuring efficient nutrient removal in wastewater treatment processes is essential for safeguarding both environmental and public health (Hasan, et. al., 2021, Rout, et. al., 2021).

The purpose of this review is to provide a comprehensive overview of emerging technologies for nutrient removal in wastewater treatment. By synthesizing recent advancements in biological, physical, and chemical treatment methods, this review aims to elucidate the potential of innovative approaches in mitigating nutrient pollution. Furthermore, the scope of the review encompasses various aspects of nutrient removal, including process principles, performance evaluations, and sustainability considerations. By examining the strengths, limitations, and potential applications of emerging technologies, this review seeks to inform researchers, practitioners, and policymakers involved in wastewater management strategies.

In summary, this review highlights the urgent need for effective nutrient removal in wastewater treatment to mitigate the adverse impacts of nutrient pollution on water quality and ecosystem health. By elucidating the significance of nutrient removal and delineating the scope of the review, we aim to contribute to the advancement of sustainable wastewater management practices through the adoption of innovative technologies and strategies.

1.1. Biological Treatment Technologies

Biological treatment technologies play a vital role in the removal of nutrients from wastewater, offering sustainable and cost-effective solutions for mitigating nutrient pollution. This review explores several emerging biological treatment methods, including the activated sludge process, sequencing batch reactors (SBRs), membrane bioreactors (MBRs), moving bed biofilm reactors (MBBRs), and integrated fixed-film activated sludge (IFAS). Through a comprehensive analysis of these technologies, we aim to elucidate their advantages, limitations, and potential applications in nutrient removal from wastewater (Kamilya, et. al., 2022, Saravanan, et. al., 2021, Sathya, et. al., 2023).

The activated sludge process is one of the most widely used biological treatment methods for wastewater treatment, renowned for its effectiveness in removing organic matter and nutrients. In this process, wastewater is aerated and mixed with a microbial culture (activated sludge) in aeration tanks, where microorganisms metabolize organic compounds and convert nitrogen and phosphorus into biomass. Subsequently, the mixed liquor is settled in clarifiers, and the clarified effluent is discharged or subjected to further treatment. The activated sludge process offers several advantages, including high removal efficiencies for organic matter and nutrients, operational flexibility, and relatively low capital costs. However, challenges such as sludge bulking, foaming, and the need for extensive maintenance and monitoring can limit its efficiency and reliability in nutrient removal.

Sequencing batch reactors (SBRs) have gained prominence as versatile and efficient biological treatment systems for wastewater. SBRs operate in batch mode, allowing for sequential phases of filling, aeration, settling, and decanting within a single reactor vessel. This cyclic operation enables optimal control over treatment conditions and facilitates biological nutrient removal through alternating anaerobic, aerobic, and anoxic conditions. SBRs offer advantages such as reduced footprint, enhanced nutrient removal efficiency, and adaptability to fluctuating influent characteristics. However, SBRs require sophisticated control systems and monitoring protocols to optimize performance, and operational challenges such as bulking, foaming, and filamentous growth can affect treatment reliability (Jagaba, et. al., 2021, Jena, et. al., 2020, Lawal, et. a., 2023).

Membrane bioreactors (MBRs) combine biological treatment processes with membrane filtration technology to achieve high-quality effluent suitable for reuse or discharge. In MBRs, microorganisms are retained within the bioreactor using ultrafiltration or microfiltration membranes, enabling biomass concentration and prolonged solids retention time. This configuration enhances nutrient removal efficiency by providing a favorable environment for biological processes while effectively removing suspended solids and pathogens. MBRs offer advantages such as compact footprint, superior effluent quality, and reduced sludge production compared to conventional activated sludge systems (Al-Asheh, Bagheri & Aidan, 2021, Monteoliva-García, et. al., 2020, Rahman, et. al., 2023). However, MBRs are susceptible to membrane fouling, which necessitates regular cleaning and maintenance, leading to increased operating costs.

Moving bed biofilm reactors (MBBRs) employ suspended biofilm carriers within aerated tanks to provide a substrate for microbial attachment and growth. As wastewater flows through the reactor, microorganisms attached to the biofilm carriers metabolize organic matter and nutrients, facilitating their removal from the wastewater stream. MBBRs offer several advantages, including high biomass retention, tolerance to hydraulic and organic load fluctuations, and minimal sludge production. Additionally, MBBRs can achieve simultaneous nitrification and denitrification, leading to efficient nitrogen removal. However, MBBRs require careful control of carrier-to-water ratios, aeration rates, and hydraulic conditions to optimize performance and prevent biofilm detachment.

Integrated fixed-film activated sludge (IFAS) systems integrate suspended growth and attached growth processes within a single treatment unit to enhance nutrient removal performance. In IFAS systems, biofilm media such as plastic carriers or structured media are incorporated into activated sludge reactors, providing a surface for microbial attachment and biofilm formation. This hybrid configuration allows for increased biomass concentration, extended solids retention time, and improved nutrient removal kinetics compared to conventional activated sludge processes. IFAS systems offer flexibility in design and operation, enabling efficient nutrient removal in both municipal and industrial wastewater treatment applications. However, challenges such as biofilm aging, clogging, and media degradation can affect system performance and require periodic maintenance (Waqas, et. al., 2023, Waqas, et. al., 2020, Zhao & Bai, 2022).

Biological treatment methods offer several advantages for nutrient removal in wastewater treatment, including high removal efficiencies, operational flexibility, and sustainability. These methods utilize natural microbial processes to metabolize organic matter and convert nutrients into biomass, thereby reducing the environmental impact of wastewater discharges. Additionally, biological treatment systems can be tailored to specific treatment goals and site conditions, making them suitable for a wide range of applications. However, biological treatment methods also have limitations, including susceptibility to process upsets, the potential for sludge bulking and foaming, and the need for extensive monitoring and maintenance. Furthermore, achieving consistent nutrient removal performance may require advanced process control strategies and supplemental treatment technologies (Machineni, 2019, Patel, et. al., 2021, Rajesh Banu, et. al., 2021).

In conclusion, biological treatment technologies play a crucial role in nutrient removal from wastewater, offering sustainable and efficient solutions for addressing nutrient pollution. The activated sludge process, sequencing batch reactors (SBRs), membrane bioreactors (MBRs), moving bed biofilm reactors (MBBRs), and integrated fixed-film activated sludge (IFAS) represent promising approaches to achieving stringent nutrient removal goals. By understanding the advantages, limitations, and operational considerations associated with these technologies, wastewater treatment professionals can make informed decisions regarding the selection, design, and optimization of biological treatment systems for nutrient removal. Continued research and development efforts are essential to further enhance the performance and reliability of emerging biological treatment methods and advance sustainable wastewater management practices.

1.2. Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) represent a group of innovative technologies that utilize powerful oxidizing agents to degrade organic pollutants and remove nutrients from wastewater. AOPs have garnered significant attention in recent years due to their ability to generate highly reactive hydroxyl radicals (•OH), which exhibit strong oxidative potential and can mineralize a wide range of organic compounds. This review explores several key AOPs, including ozonation, ultraviolet (UV) irradiation, and photocatalysis, highlighting their applications, efficiency, and challenges in nutrient removal from wastewater (Bracamontes-Ruelas, et. al., 2022, Giwa, et. al., 2021, Rekhate & Srivastava, 2020).

Ozonation involves the use of ozone (O3), a powerful oxidizing agent, to degrade organic pollutants and oxidize inorganic compounds in wastewater. Ozone is generated on-site using ozone generators and can be introduced into wastewater either as a gas or as ozone-enriched water. Upon contact with ozone, organic compounds are oxidized through direct reaction with ozone molecules or indirect reaction with hydroxyl radicals formed via ozone decomposition. Ozonation offers several advantages for nutrient removal, including rapid oxidation kinetics, broadspectrum efficacy, and minimal formation of harmful by-products. Additionally, ozone can facilitate the breakdown of recalcitrant organic molecules, enhancing the biodegradability of wastewater constituents. However, challenges such as high energy consumption, ozone mass transfer limitations, and the formation of bromate ions in bromide-containing waters can impact the efficiency and cost-effectiveness of ozonation for nutrient removal.

Ultraviolet (UV) irradiation utilizes UV light to generate reactive species, including hydroxyl radicals, through photolysis of water and other molecules in wastewater. UV irradiation can be applied either as direct UV photolysis or in combination with hydrogen peroxide (UV/H2O2) to enhance hydroxyl radical production. In direct UV photolysis, UV light with wavelengths in the germicidal range (254 nm) is absorbed by organic molecules, leading to the formation of reactive intermediates that undergo oxidation reactions. UV/H2O2 systems utilize hydrogen peroxide as a source of hydroxyl radicals, which are generated via UV-induced decomposition of hydrogen peroxide molecules (Guo, et. al., 2022, Krystynik, P. (2021, Lei, et. al., 2021). UV irradiation offers advantages such as rapid treatment kinetics, selectivity for specific target compounds, and minimal chemical usage compared to ozonation. However, UV irradiation may be less effective for treating wastewater with high turbidity or organic content, and the presence of certain compounds, such as natural organic matter, can compete for UV absorption and reduce treatment efficiency.

Photocatalysis employs semiconductor materials, such as titanium dioxide (TiO2), as photocatalysts to facilitate the generation of reactive oxygen species under UV or visible light irradiation. When illuminated, photocatalysts absorb photons and generate electron-hole pairs, which react with water and oxygen to produce hydroxyl radicals and other oxidizing species. Photocatalytic oxidation can mineralize organic pollutants, break down nitrogen and phosphorus compounds, and disinfect wastewater through oxidative mechanisms. Additionally, photocatalysis offers advantages such as versatility, scalability, and the potential for solar-driven applications. However, challenges such as limited light penetration, catalyst fouling, and the need for catalyst immobilization can affect the efficiency and practicality of photocatalytic systems for nutrient removal in wastewater treatment.

AOPs have demonstrated effectiveness in degrading a wide range of organic pollutants commonly found in wastewater, including pharmaceuticals, pesticides, and industrial chemicals (Oluwole, Omotola & Olatunji, 2020, Pandis, et. al., 2022, Titchou, et. al., 2021). The highly reactive nature of hydroxyl radicals enables AOPs to mineralize organic molecules into harmless by-products, such as carbon dioxide and water. Furthermore, AOPs can target specific organic pollutants through process optimization and catalyst selection, offering tailored solutions for wastewater treatment applications. In addition to organic pollutant degradation, AOPs have shown promise for nutrient removal from wastewater by oxidizing nitrogen and phosphorus compounds into less soluble or gaseous forms. By integrating AOPs with conventional treatment processes, such as biological treatment or membrane filtration, synergistic effects can be achieved, leading to improved overall nutrient removal efficiency.

While AOPs hold great potential for nutrient removal in wastewater treatment, several factors influence their efficiency and practical implementation. The effectiveness of AOPs depends on various factors, including wastewater composition, reactor design, operating conditions, and treatment goals. Optimal reactor configurations and process parameters must be selected to maximize hydroxyl radical production and target specific nutrient compounds effectively. Additionally, the presence of interfering substances, such as natural organic matter and inorganic ions, can affect the performance of AOPs by scavenging hydroxyl radicals or competing for oxidation reactions. Furthermore, the scalability, energy requirements, and operational costs of AOPs must be carefully evaluated to ensure economic feasibility and sustainability in real-world applications. Continued research and development efforts are essential to address these challenges and further enhance the efficiency and reliability of AOPs for nutrient removal in wastewater treatment.

In summary, advanced oxidation processes (AOPs) offer innovative solutions for nutrient removal from wastewater, leveraging powerful oxidizing agents to degrade organic pollutants and oxidize nitrogen and phosphorus compounds. Ozonation, ultraviolet (UV) irradiation, and photocatalysis represent key AOPs with distinct mechanisms and applications in wastewater treatment. While AOPs demonstrate promise for achieving stringent nutrient removal goals, challenges such as energy consumption, reactor design, and treatment optimization must be addressed to realize their full potential in sustainable wastewater management. By advancing our understanding of AOPs and optimizing their implementation, we can contribute to the development of efficient and environmentally friendly solutions for nutrient removal in wastewater treatment systems.

1.3. Membrane Technologies

Membrane technologies have emerged as effective tools for nutrient removal in wastewater treatment, offering selective separation of contaminants while producing high-quality effluent suitable for discharge or reuse. This review explores several key membrane technologies, including reverse osmosis (RO), nanofiltration (NF), and forward osmosis

(FO), highlighting their applications, advantages, and challenges in nutrient removal from wastewater (Bera, Godhaniya & Kothari, 2022, Kamali, et. al., 2019, Obotey Ezugbe & Rathilal, 2020).

Reverse osmosis (RO) is a widely utilized membrane technology that utilizes a semi-permeable membrane to separate water molecules from dissolved solutes, including salts, organic compounds, and nutrients. In RO systems, wastewater is pressurized and forced through the membrane, allowing water molecules to pass while retaining contaminants. RO membranes exhibit high rejection rates for dissolved ions and organic molecules, making them effective for nutrient removal in wastewater treatment. RO can achieve significant reductions in nitrogen and phosphorus concentrations, producing effluent with low nutrient levels suitable for discharge into sensitive environments or further treatment. Additionally, RO offers advantages such as compact footprint, scalable design, and flexibility in operation. However, RO systems require substantial energy inputs for operation, and membrane fouling can occur due to the accumulation of suspended solids, organic matter, and scaling agents, leading to reduced performance and increased operating costs (Faroon, et. al., 2023, Olusemire, 2022, Wang & Wang, 2019).

Nanofiltration (NF) is a membrane filtration process that operates at lower pressures than RO, allowing for selective separation of ions and molecules based on size and charge. NF membranes have smaller pore sizes than RO membranes, enabling the rejection of divalent ions, such as calcium, magnesium, and sulfate, while allowing monovalent ions and smaller organic molecules to pass through. NF membranes exhibit high rejection rates for nutrients, including nitrate, phosphate, and ammonia, making them suitable for nutrient removal in wastewater treatment applications. NF systems can achieve selective removal of nutrients while retaining essential ions and maintaining water quality. Additionally, NF offers advantages such as lower energy consumption, reduced fouling propensity, and compatibility with brackish water and wastewater streams. However, NF membranes are susceptible to fouling by organic matter, colloids, and biofilm formation, necessitating regular cleaning and maintenance to ensure optimal performance.

Forward osmosis (FO) is a membrane-based separation process that utilizes a concentration gradient to draw water molecules through a semi-permeable membrane from a low-concentration feed solution to a high-concentration draw solution. FO membranes selectively retain solutes, including salts and nutrients, while allowing water molecules to permeate. FO can be applied for nutrient removal by concentrating wastewater through osmotic dewatering, resulting in a reduced volume of effluent with higher nutrient concentrations. Additionally, FO systems can recover valuable resources from wastewater, such as nutrients for agricultural fertilization or energy generation through anaerobic digestion. FO offers advantages such as low energy consumption, minimal fouling propensity, and compatibility with high-salinity or challenging wastewater streams. However, FO systems may require pre-treatment to remove suspended solids and colloidal particles (Blandin, et. al., 2020, Singh, Sharma & Maiti, 2021, Xu, et. al., 2022) to prevent membrane fouling and maintain flux rates.

Membrane processes offer selective removal and concentration of nutrients from wastewater streams, enabling targeted treatment and resource recovery. RO and NF membranes can selectively reject ions based on size, charge, and molecular weight, allowing for efficient removal of nitrogen and phosphorus compounds from wastewater. By controlling operating conditions and membrane properties, membrane processes can achieve desired nutrient removal efficiencies while minimizing energy consumption and treatment costs. Additionally, membrane technologies can be integrated with biological treatment systems to enhance nutrient removal performance and effluent quality. By combining membrane filtration with biological processes, such as activated sludge or membrane bioreactors, synergistic effects can be achieved, leading to improved overall treatment efficiency and nutrient removal (Robles, et. al., 2021, Tarpeh & Chen, 2021).

The integration of membrane technologies with biological treatment systems offers synergistic benefits for nutrient removal in wastewater treatment. Membrane bioreactors (MBRs) combine biological treatment processes with membrane filtration to achieve high-quality effluent with reduced suspended solids and pathogens. MBRs enable efficient removal of nutrients through biomass retention and prolonged solids retention time, leading to enhanced nutrient removal efficiencies. Additionally, the integration of membrane technologies with biological treatment systems allows for process intensification, reduced footprint, and improved effluent quality (Molinari, Lavorato & Argurio, 2020, Noor, et. al., 2023, Ye, et. al., 2021). By optimizing system design and operation, integrated membrane-biological treatment systems can achieve stringent nutrient removal goals while minimizing energy consumption and operating costs.

Membrane fouling is a significant challenge in membrane-based wastewater treatment systems, leading to reduced flux rates, increased energy consumption, and decreased treatment efficiency. Membrane fouling can occur due to the accumulation of suspended solids, organic matter, colloids, and microbial biofilms on the membrane surface or within membrane pores. To mitigate membrane fouling, pre-treatment processes, such as coagulation, flocculation, and microfiltration, may be employed to remove particulate matter and enhance water quality. Additionally, membrane cleaning protocols, including backwashing, chemical cleaning, and air scouring, are essential for maintaining membrane performance and prolonging membrane lifespan. By implementing effective fouling control strategies and routine maintenance practices, membrane-based wastewater treatment systems can achieve optimal performance and long-term reliability.

In summary, membrane technologies offer promising solutions for nutrient removal in wastewater treatment, providing selective separation of contaminants while producing high-quality effluent suitable for discharge or reuse. RO, NF, and FO membranes can effectively remove nitrogen and phosphorus compounds from wastewater streams, offering advantages such as high rejection rates, low energy consumption, and compatibility with challenging wastewater compositions. By integrating membrane technologies with biological treatment systems and implementing fouling control strategies, membrane-based wastewater treatment systems can achieve efficient nutrient removal while minimizing operating costs and environmental impacts. Continued research and development efforts are essential to advance membrane technologies and address challenges associated with membrane fouling, energy consumption, and treatment optimization, ultimately contributing to the advancement of sustainable wastewater management practices.

1.4. Chemical Treatment Strategies

Chemical treatment strategies play a crucial role in nutrient removal from wastewater, offering effective solutions for the removal of nitrogen and phosphorus compounds. This review examines several key chemical treatment methods, including adsorption processes, precipitation methods, and ion exchange techniques, along with the utilization of novel adsorbents and nanomaterials. Additionally, the review discusses the challenges and opportunities associated with chemical treatment for nutrient removal in wastewater treatment processes (Hasan, et. al., 2021, Peng, He & Wu, 2021, Siciliano, et. al., 2020).

Adsorption processes involve the removal of contaminants from wastewater by adsorbing them onto the surface of solid adsorbents. Common adsorbents used for nutrient removal include activated carbon, zeolites, clay minerals, and biochar. These materials possess high surface areas and surface chemistries that enable them to selectively adsorb nitrogen and phosphorus compounds from wastewater. Adsorption processes offer advantages such as high removal efficiencies, versatility in adsorbent selection, and ease of operation. Additionally, adsorption can be employed as a post-treatment step to polish effluent from biological treatment processes or as a stand-alone treatment method for targeted nutrient removal (Crini, et. al., 2019, Rathi & Kumar, 2021, Sahoo & Prelot, 2020). However, challenges such as adsorbent regeneration, disposal of spent adsorbents, and scalability of adsorption systems may limit the widespread application of adsorption processes for nutrient removal.

Precipitation methods involve the addition of chemical precipitants to wastewater to form insoluble precipitates that can be removed by sedimentation or filtration. Common precipitants used for nutrient removal include metal salts, such as alum (aluminum sulfate) and ferric chloride, which react with dissolved phosphorus to form insoluble precipitates, such as aluminum or iron phosphate. Precipitation methods offer advantages such as rapid removal of phosphorus, minimal sludge production, and compatibility with existing treatment infrastructure. Additionally, precipitation can be integrated into conventional treatment processes, such as coagulation-flocculation, to enhance nutrient removal efficiency. However, challenges such as pH control, chemical dosing optimization, and the potential for residual metal concentrations in treated effluent may require careful management to ensure regulatory compliance and environmental sustainability.

Ion exchange techniques involve the removal of ions from wastewater by exchanging them with ions of similar charge on a solid ion exchange resin. Ion exchange resins can selectively remove nitrogen and phosphorus compounds from wastewater through ion exchange mechanisms. Cation exchange resins remove ammonium ions (NH4+) by exchanging them with hydrogen ions (H+), while anion exchange resins remove phosphate ions (PO4^3-) by exchanging them with hydroxyl ions (OH-). Ion exchange techniques offer advantages such as high selectivity, rapid removal kinetics, and ease of operation. Additionally, ion exchange resins can be regenerated and reused, reducing operational costs and environmental impacts (Al-Asheh & Aidan, 2020, Bashir, et. al., 2019, Lebron, et. al., 2021). However, challenges such as resin fouling, resin regeneration efficiency, and disposal of spent regenerant solutions may affect the overall performance and cost-effectiveness of ion exchange techniques for nutrient removal.

Recent advancements in materials science have led to the development of novel adsorbents and nanomaterials with enhanced adsorption capacities and selectivities for nutrient removal. These materials include graphene-based materials, carbon nanotubes, metal-organic frameworks (MOFs), and functionalized nanoparticles. Novel adsorbents and nanomaterials offer advantages such as high surface areas, tunable surface chemistries, and unique adsorption mechanisms, making them promising candidates for targeted nutrient removal in wastewater treatment. Additionally, the synthesis of nanomaterials with specific functionalities, such as photocatalytic or magnetic properties, enables multifunctional treatment approaches for nutrient removal and resource recovery (Chai, et. al., 2021, Rajendran, et. al., 2022, Zhou, et. al., 2019). However, challenges such as scalability, cost-effectiveness, and environmental impacts of nanomaterial production and disposal require further research and development to realize their full potential in wastewater treatment applications.

Chemical treatment strategies offer effective solutions for nutrient removal in wastewater treatment, but they also present challenges that must be addressed to optimize treatment efficiency and sustainability (Dutta, Arya & Kumar, 2021, Guven, et. al., 2019, Shah, et. al., 2020). Challenges such as chemical dosing optimization, by-product formation, and residual chemical concentrations in treated effluent may require advanced process control strategies and monitoring protocols to ensure regulatory compliance and environmental protection. Additionally, the integration of chemical treatment processes with biological treatment systems or membrane technologies offers opportunities for synergistic effects and improved overall treatment performance. By leveraging the strengths of different treatment methods and optimizing their integration, wastewater treatment plants can achieve efficient nutrient removal while minimizing energy consumption, chemical usage, and environmental impacts. Continued research and innovation in chemical treatment technologies are essential to address emerging challenges and advance sustainable nutrient removal practices in wastewater treatment.

1.5. Process Optimization and System Integration

Efficient removal of nutrients from wastewater is essential to mitigate the adverse environmental and public health impacts associated with nutrient pollution. Process optimization and system integration play pivotal roles in enhancing nutrient removal efficiency, minimizing resource consumption, and ensuring the sustainability of wastewater treatment operations. This review explores the importance of optimization in nutrient removal, the integration of multiple treatment processes, the application of life cycle assessments (LCAs) and techno-economic analyses, and environmental sustainability considerations in wastewater treatment systems (Emparan, Harun & Danquah, 2019, Kamilya, et. al., 2022, Shortle, et. al., 2020).

Optimization of wastewater treatment processes is crucial for maximizing nutrient removal efficiency while minimizing resource consumption and operating costs. By fine-tuning operational parameters, such as hydraulic retention time, solids retention time, aeration rates, and chemical dosing rates, treatment plants can achieve optimal nutrient removal performance. Process optimization involves the application of advanced process control strategies, real-time monitoring and data analytics, and predictive modeling techniques to optimize treatment performance and ensure compliance with regulatory standards. Additionally, optimization efforts may include the implementation of innovative technologies, such as sensor-based control systems, artificial intelligence algorithms, and machine learning algorithms, to enhance process efficiency and reliability. By continuously optimizing treatment processes, wastewater treatment plants can improve nutrient removal efficiency, reduce energy and chemical usage, and minimize environmental impacts.

Integration of multiple treatment processes offers synergistic benefits for comprehensive nutrient removal in wastewater treatment systems. By combining biological, physical, and chemical treatment methods, treatment plants can address the complex nature of nutrient pollution and achieve higher removal efficiencies than single-stage treatment approaches (Rajesh Banu, et. al., 2020, Zhou, et. al., 2022). For example, integrating biological treatment systems, such as activated sludge or membrane bioreactors, with advanced oxidation processes (AOPs) or membrane filtration technologies can enhance nutrient removal performance and produce high-quality effluent for discharge or reuse. Additionally, sequential treatment trains, such as biological-nitrification-denitrification-phosphorus removal (BNDRP) processes, can optimize nutrient removal kinetics and minimize the formation of harmful by-products. By strategically integrating complementary treatment processes, treatment plants can tailor treatment strategies to specific wastewater compositions and treatment goals, leading to more effective nutrient removal and improved overall treatment performance.

Life cycle assessments (LCAs) and techno-economic analyses are valuable tools for evaluating the environmental and economic sustainability of wastewater treatment processes. LCAs assess the environmental impacts of treatment processes, including energy consumption, greenhouse gas emissions, water usage, and waste generation, throughout their life cycles, from raw material extraction to end-of-life disposal. Techno-economic analyses, on the other hand, evaluate the economic feasibility and cost-effectiveness of treatment technologies by considering capital and operating costs, energy and chemical consumption, maintenance requirements, and revenue streams. By conducting comprehensive LCAs and techno-economic analyses, decision-makers can identify opportunities for process optimization, technology substitution, and resource recovery, leading to more sustainable and cost-effective wastewater treatment solutions. Additionally, LCAs and techno-economic analyses provide valuable insights for policy-makers, regulators, and stakeholders in evaluating the environmental and economic implications of different treatment options and guiding investment decisions in wastewater infrastructure.

Environmental sustainability considerations are essential for designing and operating wastewater treatment systems that minimize environmental impacts and protect natural ecosystems (Mihelcic & Zimmerman, 2021, Su, et. al., 2019, Yenkie, 2019). Sustainable wastewater management practices prioritize resource conservation, energy efficiency, and pollution prevention, while promoting ecosystem resilience and biodiversity conservation. Key environmental sustainability considerations for nutrient removal in wastewater treatment include minimizing energy and chemical usage, reducing greenhouse gas emissions, conserving water resources, and minimizing the release of harmful by-products and pollutants into the environment. Additionally, sustainable wastewater management practices incorporate principles of circular economy and resource recovery, such as nutrient recycling, bioenergy generation, and wastewater reuse for irrigation or industrial processes. By adopting environmentally sustainable approaches to nutrient removal, wastewater treatment plants can minimize their ecological footprint, enhance environmental stewardship, and contribute to the transition to a more sustainable and resilient water infrastructure.

In conclusion, process optimization and system integration are essential strategies for enhancing nutrient removal efficiency, minimizing resource consumption, and ensuring the sustainability of wastewater treatment operations. By optimizing treatment processes, integrating complementary treatment technologies, conducting comprehensive LCAs and techno-economic analyses, and prioritizing environmental sustainability considerations, wastewater treatment plants can achieve higher nutrient removal efficiencies, reduce operating costs, and minimize environmental impacts. Continued research, innovation, and collaboration are essential to advance sustainable nutrient removal practices and promote the transition to more resilient and environmentally sustainable wastewater treatment systems.

2. Future Research Directions

As the global demand for clean water continues to rise and environmental regulations become increasingly stringent, there is a growing need for sustainable and efficient nutrient removal technologies in wastewater treatment. Future research directions in this field aim to address key challenges, such as scalability and applicability of emerging technologies, energy efficiency and resource recovery opportunities, holistic approaches towards sustainable wastewater management, and the mitigation of emerging contaminants and pollutants. By focusing on these areas, researchers can develop innovative solutions to enhance nutrient removal efficiency, minimize environmental impacts, and promote the transition to more sustainable wastewater treatment practices (Ahmad, et. al., 2022, Vasantha & Jyothi, 2020, Werkneh & Gebru, 2023).

One of the primary challenges in the implementation of emerging nutrient removal technologies is ensuring scalability and applicability across different wastewater treatment settings. While many innovative technologies show promise at the laboratory or pilot scale, scaling up to full-scale applications can present technical, economic, and logistical challenges. Future research should focus on developing scalable and adaptable technologies that can be easily integrated into existing wastewater treatment infrastructure. Additionally, research efforts should explore the performance of emerging technologies under varying operating conditions, wastewater compositions, and environmental factors to assess their robustness and reliability in real-world applications. By addressing scalability and applicability challenges, researchers can accelerate the adoption of emerging nutrient removal technologies and enhance their impact on global water quality management.

Energy consumption is a significant operational cost in wastewater treatment plants, and reducing energy usage is critical for improving the sustainability of nutrient removal processes. Future research should focus on developing energy-efficient nutrient removal technologies that minimize energy consumption while maintaining high treatment performance. This may involve optimizing process design, implementing energy recovery systems, and exploring alternative energy sources, such as renewable energy and waste heat utilization. Additionally, there is a growing interest in resource recovery from wastewater, including the recovery of nutrients, bioenergy, and valuable materials (Capodaglio & Olsson, 2019, Ghimire, Sarpong & Gude, 2021, Guven, et. al., 2019). Future research should explore innovative approaches for nutrient recovery, such as struvite precipitation, algae cultivation, and anaerobic digestion, to maximize resource utilization and minimize waste generation in wastewater treatment processes. By prioritizing energy efficiency and resource recovery opportunities, researchers can develop more sustainable and cost-effective nutrient removal technologies that contribute to the circular economy and reduce environmental impacts.

Achieving sustainable wastewater management requires a holistic approach that considers the entire wastewater treatment process, from influent to effluent, as well as the broader environmental and socio-economic context. Future research should focus on integrating nutrient removal technologies into holistic wastewater management frameworks that prioritize environmental sustainability, public health, and social equity. This may involve adopting decentralized treatment systems, optimizing water reuse and recycling practices, and implementing nature-based solutions, such as constructed wetlands and green infrastructure. Additionally, research efforts should explore the potential synergies and trade-offs between different treatment processes, such as biological, physical, and chemical treatment methods, to develop integrated and optimized treatment strategies. By embracing holistic approaches towards sustainable wastewater management, researchers can develop resilient and adaptive solutions that address the complex challenges of nutrient pollution while enhancing ecosystem health and human well-being.

In addition to traditional nutrients such as nitrogen and phosphorus, wastewater treatment plants are increasingly facing challenges associated with emerging contaminants and pollutants, including pharmaceuticals, personal care products, microplastics, and industrial chemicals (Khan, et. al., 2022, Mishra, et. al., 2023, Yadav, et. al., 2021). Future research should focus on developing innovative treatment technologies that can effectively remove these emerging contaminants while minimizing the generation of harmful by-products and secondary pollutants. This may involve the development of advanced oxidation processes, membrane filtration technologies, and biological treatment methods tailored to specific contaminants of concern. Additionally, research efforts should explore the fate and transport of emerging contaminants in wastewater treatment systems, as well as their potential impacts on human health and the environment. By addressing emerging contaminants and pollutants, researchers can enhance the resilience and effectiveness of wastewater treatment systems and ensure the protection of water resources for future generations.

In conclusion, future research directions in nutrient removal technologies for wastewater treatment should focus on addressing key challenges such as scalability and applicability, energy efficiency and resource recovery, holistic wastewater management, and emerging contaminants and pollutants. By prioritizing these research areas, researchers can develop innovative solutions to enhance nutrient removal efficiency, minimize environmental impacts, and promote the transition to more sustainable wastewater treatment practices. Continued collaboration between researchers, practitioners, policymakers, and stakeholders is essential to accelerate progress towards achieving global water quality goals and ensuring the long-term sustainability of wastewater treatment systems.

3. Conclusion

In this review, we have explored a range of emerging technologies for nutrient removal in wastewater treatment, including biological treatment methods, advanced oxidation processes, membrane technologies, chemical treatment strategies, and process optimization approaches. Through a comprehensive analysis of these technologies, several key findings have emerged.

Firstly, biological treatment methods such as activated sludge processes, sequencing batch reactors, and membrane bioreactors offer efficient and sustainable solutions for nutrient removal, with the potential for enhanced performance through process optimization and system integration. Secondly, advanced oxidation processes such as ozonation, ultraviolet irradiation, and photocatalysis show promise for targeted removal of nutrients and organic pollutants, but challenges such as energy consumption and membrane fouling must be addressed for practical implementation. Thirdly, membrane technologies including reverse osmosis, nanofiltration, and forward osmosis offer selective removal of nutrients and contaminants, with opportunities for resource recovery and energy efficiency through process optimization and integration with biological treatment systems. Fourthly, chemical treatment strategies such as adsorption processes, precipitation methods, and ion exchange techniques provide effective means of nutrient removal, but further research is needed to optimize their performance and minimize environmental impacts.

Overall, these emerging technologies hold significant implications for wastewater treatment practices, offering opportunities to improve nutrient removal efficiency, minimize environmental impacts, and enhance the sustainability of wastewater treatment operations. By integrating these technologies into holistic wastewater management frameworks and prioritizing energy efficiency, resource recovery, and environmental sustainability, wastewater treatment plants can optimize nutrient removal processes and meet increasingly stringent regulatory requirements.

Looking ahead, future research should focus on addressing key challenges such as scalability, energy efficiency, and the mitigation of emerging contaminants, while exploring opportunities for innovation and technology transfer. Collaboration between researchers, practitioners, policymakers, and stakeholders is essential to accelerate progress towards achieving global water quality goals and ensuring the long-term sustainability of wastewater treatment systems. Recommendations for future research and implementation include:

Further investigation into the scalability and applicability of emerging technologies across different wastewater treatment settings. Continued efforts to improve energy efficiency and explore opportunities for resource recovery in nutrient removal processes. Development of holistic approaches towards sustainable wastewater management, considering environmental, economic, and social dimensions. Exploration of innovative solutions for addressing emerging contaminants and pollutants in wastewater treatment processes. Collaboration and knowledge sharing between researchers, practitioners, policymakers, and stakeholders to promote the adoption of emerging technologies and best practices in nutrient removal.

In conclusion, the advancement of emerging technologies for nutrient removal in wastewater treatment holds great promise for improving water quality, protecting public health, and safeguarding the environment. By embracing innovation, collaboration, and sustainability principles, the wastewater treatment sector can continue to evolve and meet the evolving challenges of nutrient pollution in the 21st century.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest is to be disclosed.

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