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Navigating the nitrogen challenge: Strategies for wastewater management and sustainable resource recovery

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Abstract. Water scarcity and the impact of nitrogen pollution from wastewater have emerged as pressing global concerns. This study delved into the hazards posed by nitrogen pollution, focusing on its sources, composition, and detrimental effects on both the environment and the agricultural sector. The primary research methodology involved a comparative analysis of various nitrogen control and recovery technologies, highlighting the technical effects and future application prospects of ammonia vapor stripping and adsorption nitrogen recovery. Findings revealed that while ammonia vapor stripping offers operational simplicity, it is energy-intensive and requires careful byproduct management. In contrast, adsorption nitrogen recovery provides a more energy-efficient method, though challenges like selectivity in the presence of contaminants persist. The study concludes by suggesting an integrated approach that combines both methods, optimized based on wastewater characteristics, and underscores the importance of byproduct valorization and the development of selective adsorbents. The ultimate goal is to ensure sustainable environmental solutions while maximizing resource optimization.

Keywords: Nitrogen, Nitrogen Pollution, Nitrogen Recovery.

1. Introduction

Water is one of the most valuable resources on Earth and plays an indispensable role in human survival and development. The importance of water is self-evident as it is crucial in sustaining livelihoods, agriculture, and industry and is the basic structure of the ecosystem. However, with rapid global population growth and urbanization, water availability is facing increasing challenges. Urbanization has led to overexploitation and pollution of water resources, making water scarcity a growing problem [1]. At the same time, municipal wastewater discharge is facing serious challenges.

Currently, directives on municipal wastewater treatment remain outdated and cannot cope with the ever-changing levels of fine-grained pollution. Worryingly, up to 80% of municipal and industrial wastewater is discharged into the environment without treatment [1]. The rapid growth of cities and the high costs associated with wastewater treatment exacerbate the problem. This negligence is evident in both urban and rural areas [2]. These wastewaters contain organic matter, nitrogen, and phosphorus, which can pollute rivers, lakes, and coastal areas. Such pollution severely affects human health and the wider ecosystem [3]. Furthermore, the presence of harmful chemicals, viruses, and bacteria in untreated wastewater escalates the risk, underscoring the urgent need for effective wastewater management solutions to protect our environment.

Nitrogen pollution, as one of the critical issues in wastewater treatment, is a growing concern because of its profound impact on the environment. Nitrogen-rich wastewater poses a threat to aquatic ecosystems when it is discharged indiscriminately into the environment. It is a catalyst for eutrophication, characterized by the rampant growth of algae and aquatic plants. This explosive growth, in turn, depletes the oxygen levels in the water, endangering aquatic life. However, the impact of nitrogen pollution goes far beyond water bodies. It adversely affects agricultural yields and leads to soil degradation. Agriculture is already a significant contributor of nitrogen, and with the addition of non-point source pollution from urban and industrial areas, the challenges ahead can be imagined [4].

Because of the growing global concern over water scarcity and the urgent need for efficient water management, this study delves into the nitrogen pollution caused by wastewater. By focusing on the hazards of nitrogen pollution, the study aims to elucidate the sources, composition, and specific hazards of nitrogen in wastewater, including its impact on the environment and the agricultural sector. In addition, the study will provide an overview and comparative analysis of various nitrogen control and recovery technologies. A particular emphasis will be placed on Chinese government policies and legal constraints related to nitrogen management, complemented by case studies exploring the application of cutting-edge nitrogen removal technologies in different regions. Ultimately, this research aims to contribute to sustainable environmental solutions and better public health outcomes while identifying potential avenues for future exploration and technological advancement in wastewater management.

2. Nitrogen in wastewater

2.1. Sources of nitrogen in wastewater

Nitrogen pollution is a significant problem in waterways and can come from various sources, including domestic wastewater, industrial wastewater, agricultural runoff, and stormwater runoff.

(1) Domestic Wastewater

Domestic wastewater is generated from households, commercial establishments, and institutions. It contains various pollutants, including nitrogen, which can cause water pollution if not treated properly. Nitrogen in domestic wastewater comes from human waste, food waste, and cleaning agents. When domestic wastewater is discharged into waterways without proper treatment, it can cause eutrophication, which is the excessive growth of algae and other aquatic plants due to the high nutrient content [5].

(2) Industrial Wastewater

Industrial wastewater is generated from various industries, including manufacturing, mining, and power generation. It contains various pollutants, including nitrogen, which can cause water pollution if not treated properly. Nitrogen in industrial wastewater comes from various sources, including cooling water, process water, and cleaning agents. When industrial wastewater is discharged into waterways without proper treatment, it can cause eutrophication, which is the excessive growth of algae and other aquatic plants due to the high nutrient content [5].

(3) Agricultural Runoff & Stormwater Runoff

Agricultural runoff and stormwater runoff are significant sources of nitrogen pollution in waterways. Agricultural runoff occurs when rainwater or irrigation water runs off agricultural land, carrying various pollutants, including nitrogen. Nitrogen in agricultural runoff comes from various sources, including animal manure and chemical fertilizers. When agricultural runoff enters waterways, it can cause eutrophication, which is the excessive growth of algae and other aquatic plants due to the high nutrient content [6]. Similarly, stormwater runoff occurs when rainwater or snowmelt runs off from urban areas, carrying with it various pollutants, including nitrogen. Nitrogen in stormwater runoff comes from various sources, including fertilizers, pet waste, and vehicle exhaust. When stormwater runoff enters waterways, it can cause eutrophication, which is the excessive growth of algae and other aquatic plants due to the high nutrient content [7].

In conclusion, nitrogen pollution is a significant problem in waterways and can come from various sources, including domestic wastewater, industrial wastewater, agricultural runoff, and stormwater runoff. It is essential to manage these sources of nitrogen pollution to protect water quality and prevent eutrophication.

2.2. *The necessity of nitrogen recovery*

2.2.1. Hazards of Nitrogen Resources. Excessive nitrogen in aquatic ecosystems can lead to several detrimental environmental and human health effects. Overabundant nitrogen can prompt the rapid growth of plants and algae, resulting in dense blooms that obstruct water intakes, diminish oxygen supply, and block sunlight for other aquatic beings [8]. This overgrowth, combined with the subsequent decay of algae, can cause eutrophication, leading to oxygen depletion and harming aquatic life such as fish, crabs, and oysters. Moreover, certain algae thriving in nitrogen-rich waters produce toxins detrimental to humans and wildlife. These toxins can accumulate in filter-feeding shellfish, prompting closures of shellfishing areas and posing economic challenges [9].

Nitrogen pollution directly threatens human health, mainly when it contaminates drinking water. High nitrate levels can cause methemoglobinemia or "blue baby syndrome" in infants, associated with cancers, reproductive issues, hypothyroidism, and other health conditions [10]. Additionally, excessive nitrogen can severely disrupt the ecological balance of water ecosystems, leading to biodiversity loss. As fast-growing plants and algae suppress the growth of other beneficial aquatic plants, it can trigger cascading impacts on the entire ecosystem, altering the food chain and overall ecological health. To safeguard the environment, aquatic life, and human health, it is imperative to manage and curtail nitrogen pollution through wastewater treatment, reduce agricultural runoff, and adopt best management practices [11].

Controlling and recovering nitrogen is essential for protecting the environment, ensuring safe drinking water, and maintaining agricultural productivity. Nitrogen recovery can also provide a sustainable source of nitrogen for agricultural uses.

2.2.2. Use of Nitrogen Resources. The risks of nitrogen pollution can be reduced with the help of effective nitrogen recovery from wastewater, which also offers a number of advantages. It is possible to extract nitrogen and transform it into useful goods like fertilizer, biogas, or medications. Nitrogen is a valuable resource. Living things require the elements nitrate (N), phosphorus (P), and potassium (K) to grow. In modern agriculture, these nutrients are provided as fertilizers to restore soil fertility, preserve nutrient reserves, and boost food output [12].

For fertilizer use, NH3 is commonly produced from fossil fuels, primarily natural gas. The Haber-Bosch process accounts for approximately 80% of global NH3 production. However, some studies have indicated that this process has several downsides, such as being energy expensive, needing high temperatures and pressures, and generating substantial volumes of carbon dioxide, a greenhouse gas that contributes to climate change [13]. Furthermore, it is dependent on nonrenewable materials, which may become rare and expensive in the future. In general, short-circuiting the nitrogen cycle is theoretically doable but not very energy-efficient. Current and future technologies are uncompetitive in terms of cost because of the massive amounts of chemicals required. In exceptional circumstances, nitrogen recycling with residual chemicals or waste heat can be cost-effective and sustainable. New methods that consume less electricity, heat, and chemicals are required in the future to enable more competitive and viable nitrogen recovery techniques for WWTP side streams [14].

3. Nitrogen recovery technologies

In recent years, the main approaches to nitrogen management have been to control nitrogen releases and mitigate the environmental impact of nitrogen. While these measures are undeniably essential, such importance often overshadows the equally critical aspect of nitrogen recovery. Recovering nitrogen prevents it from becoming a pollutant and allows it to be reused as a valuable resource for various purposes. However, current discussions need to pay more attention to this critical component. This paper attempts to do so by delving into and analyzing the different methods of effectively recovering nitrogen

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within the framework of a broader nitrogen control strategy. By highlighting these methods, we can shift the focus from control alone to a more holistic approach that combines power and recovery to ensure environmental protection and resource optimization.

(1) Ammonia Stripping

Ammonia stripping is foundational in the Nitrogen Recovery and Removal (NRR) sector. By elevating the pH of wastewater laden with NH4-N, ammonia is converted into volatile NH3, which subsequently vaporizes. This ammonia is then captured using acidic solutions like sulphuric acid, resulting in ammonium sulfate, a potential fertilizer [15]. The method's efficacy is influenced by pH, temperature, and contaminant concentration [16]. This process can recover 70–92% of nitrogen from wastewater [17]

(2) Adsorption and Ion Exchange

Adsorption is crucial, particularly for wastewater with diluted ammonium content. This approach primarily utilizes carbon-based adsorbents or porous solids, such as zeolites and activated charcoal [18]. Modified zeolites boast enhanced adsorption capacities and can be directly applied to farmlands as slow-release fertilizers [17]. Further studies have showcased the potential of materials like plagioclase zeolite in achieving nitrogen recovery rates between 65-80% [17].

Ion exchange offers a distinctive methodology where cation exchange resins are paramount in trapping ammonium ions. These ions are then released into a concentrated solution during regeneration [19]. Depending on resin type, influent concentration, and operational conditions, recovery rates can range from 70% to 99%. Specific studies focusing on urine recovery have reported a 90% recovery rate for ammonia [17].

(3) Bio-electrochemical Systems

BES, encompassing technologies like MEC, MFC, and MDC, harness the combined potential of microorganisms and electricity—factors like current density, cathode electrolyte pH, and ion concentration influence ammonia recovery. Under specific conditions, BES can achieve nitrogen recovery rates of up to 45.3% [20]. An innovative electrochemical plant, fusing electro-concentration and vapor stripping, has demonstrated the capability to achieve nitrogen recoveries of 87% [15].

4. Discussion

4.1. Discussion of technical effects and application prospects

The comparative analysis of ammonia vapor stripping and adsorption nitrogen recovery reveals a nuanced understanding of their potential advantages and limitations. Ammonia vapor stripping, noted by the EPA (2000), offers operational simplicity and resilience to wastewater fluctuations under stable pH and temperature. However, its reliance on elevated pH and temperature contributes to escalated operational costs and energy consumption [21]. The emission of ammonia gas necessitates careful collection and treatment to prevent environmental and health risks. Moreover, the concentrated ammonia solution generated requires appropriate disposal strategies. Despite its operational ease, the method's energy consumption, byproduct management, and economic implications warrant careful consideration.

In contrast, adsorption nitrogen recovery, per Zhou et al. (2023), presents the prospect of producing high-purity nitrogen through an energy-efficient, ambient-pressure process [2]. The utilization of cost-effective adsorbents enhances its appeal, though challenges emerge. The need for substantial adsorbent quantities increases capital and space requirements. The method's efficiency might diminish in the presence of diverse contaminants, impacting selectivity. The production of secondary pollutants necessitates proper handling. While its environmental and economic benefits are evident, addressing practical challenges and optimizing adsorption under varying wastewater compositions is crucial.

These methods hold application potential, with ammonia vapor stripping suitable for industries with stable wastewater conditions and high ammonia concentrations. Adsorption nitrogen recovery can cater to industries requiring high-purity nitrogen, especially in scenarios with energy and cost considerations. Addressing challenges such as byproduct management and selectivity will determine their successful implementation [22].

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4.2. Suggestions
Consider an integrated approach combining ammonia vapor stripping and adsorption nitrogen recovery based on wastewater characteristics. Optimize ammonia vapor stripping conditions to reduce energy-intensive pH and temperature requirements. Explore byproduct valorization strategies, converting ammonia gas and repurposing spent adsorbents to minimize waste. Develop selective adsorbents for efficient nitrogen removal in complex wastewater streams. Innovate energy-efficient regeneration methods for adsorbents. Conduct holistic life-cycle assessments to evaluate environmental impacts and sustainability. Investigate technology combinations like pairing adsorption nitrogen recovery with bio-electroconcentration for enhanced efficiency. Validate findings through pilot-scale studies under real-world conditions to inform practical nitrogen removal decisions.

5. Conclusion
The research conducted has underscored the paramount importance of water in maintaining ecological balance and supporting human existence. A critical concern highlighted was the pervasive issue of nitrogen pollution from wastewater, exacerbated by the dual forces of rapid urbanization and outdated wastewater treatment methodologies. The findings indicated that the traditional focus on merely controlling nitrogen release is inadequate. Instead, there is a compelling need to recover nitrogen, transforming it from a potential pollutant into a valuable asset. In-depth evaluations of techniques such as ammonia stripping, adsorption, and bio-electrochemical systems were carried out. Each method, while promising, presented its unique set of challenges. Among these, energy consumption and byproduct management stood out as recurrent issues. The comparative examination of ammonia vapor stripping and adsorption nitrogen recovery provided a nuanced understanding, revealing their specific strengths and areas needing improvement.

This research offers a paradigm shift in wastewater management, emphasizing the potential economic and environmental benefits of nitrogen recovery. By repurposing wastewater as a resource, industries can achieve both economic optimization and a reduced environmental footprint.

Building on the foundation laid by this study, there's a promising avenue for exploring integrated nitrogen recovery techniques. The scalability and adaptability of these methods, especially in burgeoning urban areas, warrant further investigation. Future endeavors can also delve deeper into innovative technologies, ensuring a sustainable approach to wastewater management.

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