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VIETNAM ACADEMY SCIENCE AND TECHNOLOGY

GRADUATE UNIVERSITY SCIENCE AND TECHNOLOGY

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REMOVAL OF AMMONIA FROM NITROGEN-RICH WASTEWATER USING THE HIGH CENTRIFUGAL HP2R SYSTEM (HIGH-PERFORMANCE ROTATING REACTOR)

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ABSTRACT

1. Research motivation

Ammonia is a common and difficult-to-treat pollutant in wastewater from industrial, agricultural, and solid waste treatment sources, especially in livestock wastewater and landfill leachate. Various technologies have been studied and applied, such as biological treatment, chemical coagulation, adsorption, ion exchange, membrane filtration, and stripping. However, most are only effective when ammonia concentrations are below 200 mg/L. Biological processes are affected by imbalanced C/N ratios, leading to microbial inhibition. Adsorption and ion exchange require frequent material replacement, increasing costs. Chemical coagulation consumes large amounts of chemicals and generates secondary sludge. Membrane filtration demands large module systems, incurs high costs, and faces challenges in treating concentrated brine. Stripping, which removes NH_3 by adjusting pH and temperature, is more suitable for high-ammonia wastewater. However, to achieve high efficiency at large capacities, conventional equipment requires large dimensions or multiple parallel towers, resulting in higher costs and land use.

The principle of high-gravity (HiGee) technology has been applied to enhance mass transfer rates, reduce equipment volume, shorten retention time, and improve treatment efficiency. HiGee-based devices are a potential alternative to conventional stripping towers, overcoming limitations in size, cost, and performance. This study evaluates ammonia stripping using a High Performance Rotating Reactor (HP2R) applying the HiGee principle for three types of wastewater: synthetic, livestock, and landfill leachate. Experiments

focus on investigating the effects of centrifugal speed, gas flow rate (Q_G), liquid flow rate (Q_L), pH, and temperature, as well as calculating the liquid-phase volumetric mass transfer coefficient (K_La) and stripping efficiency (η) to establish predictive models. The study also assesses the potential for NH_3–N recovery after stripping, aiming to develop a treatment–recovery process aligned with circular economy and sustainability goals.

2. Research Objectives

- Investigate and evaluate factors affecting the stripping and recovery of high-concentration NH_3–N from wastewater using the HP2R.
- Optimize operating conditions of the HP2R for high-ammonia wastewater treatment and recovery. Propose a technological system for wastewater treatment and resource recovery in line with the circular economy approach.

3. Main Research Contents

- Investigate factors affecting ammonia stripping in the HP2R from synthetic wastewater, livestock wastewater, and landfill leachate.
- Calculate stripping efficiency, liquid-phase overall mass transfer coefficient, and develop predictive models for ammonia stripping performance using the HP2R..
- Conduct combined treatment and ammonia recovery experiments from synthetic wastewater and landfill leachate using the HP2R.
- Calculate stripping efficiency, ammonia recovery efficiency, and develop kinetic models for the combined treatment–recovery process.
- Conduct preliminary techno-economic evaluation and propose application models of the centrifugal contact principle for ammonia treatment and recovery from wastewater at real-world scales.

CHAPTER 1. OVERVIEW

1.1. Ammonium in Wastewater

1.1.1. General overview of ammonium/ammonia

A general introduction to ammonium/ammonia (NH_4^+/NH_3) is provided, including their role, physicochemical properties, and distribution within the nitrogen biogeochemical cycle. This section also discusses factors affecting the NH_4^+/NH_3 equilibrium, their impacts on the environment and human health.

1.1.2. Ammonium in wastewater

This section summarizes the characteristics, role, and equilibrium mechanisms of NH_4^+/NH_3 in the aquatic environment, factors influencing them, and their ecological and health impacts. It also presents the current status of ammonium pollution, especially in areas affected by agriculture, industry, and landfills.

1.1.3. Harmful effects of ammonium in aquatic environments

NH_4^+ has adverse effects on aquatic life, human health, and water quality—even at low concentrations—through direct toxicity, eutrophication, corrosion of water supply infrastructure, and the risk of forming carcinogenic nitrosamines.

1.2. Ammonium Removal Technologies in Wastewater

1.2.1. Biological treatment

Biological methods have the advantage of low cost since they mainly rely on microbial degradation. However, limitations include relatively long cultivation times, significant hydraulic retention times, and sensitivity to operational changes such as temperature and influent composition. For wastewater with a low C/N ratio, such as livestock wastewater and anaerobically treated landfill leachate, biological treatment efficiency is often inhibited.

1.2.2. Chemical precipitation

Struvite precipitation offers high NH_4^+ removal efficiency, rapid and stable operation, and recovery of N and P as slow-release fertilizers. It performs well at neutral to slightly alkaline pH, is tolerant to excess MgO, but depends heavily on the N:P molar ratio and the concentration of PO_4^{3-} in wastewater. The presence of Ca^{2+} or lack of phosphorus significantly reduces efficiency.

1.2.3. Ion exchange

Ion exchange can effectively treat a wide range of ammonium concentrations, but operating costs are high due to resin regeneration requirements. Desorption can also occur when influent concentration decreases. This method is suitable for tertiary treatment using low-cost media, to ensure stable performance and minimize the effects of competing cations.

1.2.4. Adsorption

Adsorption is a low-cost, simple-to-operate method for ammonium removal that avoids secondary pollution and can use various materials such as activated carbon, zeolites, or nanomaterials for high efficiency. However, performance may decline due to competing ions, organic matter, pore blockage, or material degradation. Regeneration is costly and generates secondary waste streams.

1.2.5. Membrane filtration

Membrane technologies, especially hollow fiber membrane contactors, can achieve very high NH_4^+/NH_3 removal efficiency, with short treatment times, no secondary pollution, low-pressure operation, and suitability for a wide concentration range. Main drawbacks include high capital and maintenance costs, limited membrane lifespan, and fouling-related blockages.

1.2.6. Stripping

Stripping achieves outstanding NH_4^+/NH_3 removal efficiency (up to 98%), stable operation, easy control, and independence from biological processes. However, it requires high pH, suitable temperature, and optimal gas-to-liquid ratio (Q_G/Q_L), leading to high chemical and energy consumption and potential clogging of packed columns with large gas flow rates.

1.2.7. Comparison of ammonium removal methods

At high concentrations, biological, adsorption, ion exchange, coagulation, and membrane methods are constrained by efficiency, cost, and operation. Stripping, in contrast, depends on hydrodynamic and physical conditions rather than influent ammonium concentration, making it suitable for pretreating high-strength ammonium before applying other methods.

1.3. Trends in Wastewater Treatment with Resource Recovery

1.3.1. Trends in ammonium recovery from wastewater

Global demand for ammonia is rising sharply due to fertilizer production for food security, mostly based on the Haber–Bosch process, which consumes 1–2% of global energy and emits large amounts of greenhouse gases, disrupting the nitrogen cycle. Current trends shift from “removal” to “recovery” of nutrients, utilizing ammonium and nitrogen compounds in wastewater to produce fertilizers in a circular and sustainable manner.

1.3.2. Potential of ammonium recovery from wastewater via stripping

Stripping–absorption can recover over 90% of ammonium from high-strength wastewater (>1000 mg/L) by converting NH_4^+ to NH_3 under alkaline pH and absorbing it into ammonium sulfate solution, simultaneously treating wastewater and producing valuable fertilizer.

1.3.3. Drawbacks of conventional stripping towers

Conventional stripping towers use large packed columns to increase gas–liquid contact area and time, improving NH_3 separation efficiency. However, they require large equipment size and high investment. Thus, improved or alternative equipment is needed to overcome these limitations for high-strength ammonium treatment and recovery.

1.4. Overview of Centrifugal Contacting Technology and Applications for Mass Transfer Enhancement

1.4.1. History and principles of centrifugal contacting technology

Efforts to overcome the limitations of conventional absorption and stripping towers have driven research into using high-gravity fields to enhance gas–liquid mass transfer. While the principle was mentioned in some early 20th-century studies, it was not until 1981 that Ramshaw and Mallinson first patented a rotating packed bed (RPB) contactor, demonstrating the feasibility of centrifugal contacting technology.

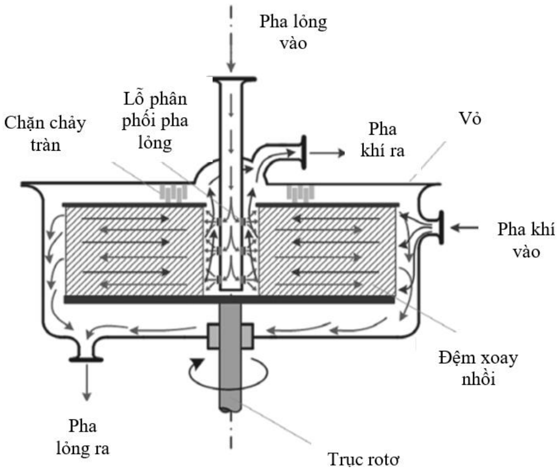


Figure 1.1. Principle of RPB equipment

1.4.2. Some hydraulic characteristics of centrifugal mass transfer processes

Key hydraulic characteristics in HiGee devices include: Pressure drop, Liquid flow patterns, Liquid holdup, Hydraulic retention time, Flooding point

1.4.3. Applications of centrifugal contactors

a, Research applications: HiGee (RPB) devices have been effectively applied to stripping ammonium, VOCs, ethanol, and ClO_2 from water, as well as CO_2 and VOC absorption from flue gas.

b, Industrial application: Deaeration of seawater, reactive stripping of hypochlorous acid, SO_2 removal, selective H_2S absorption, deaeration in bottled beverage production, and separation processes in distillation.

1.5. Necessity of Applying Centrifugal Technology in High-Ammonium Wastewater Treatment in Vietnam

1.5.1. Current research and application status in Vietnam

In Vietnam, treatment of high-strength ammonium wastewater (e.g., landfill leachate, livestock wastewater) often prioritizes stripping, as biological and adsorption methods are ineffective in such conditions. Stripping is widely applied for pretreatment due to high efficiency and low chemical use, but large equipment size, high investment, and risk of NH_3 emissions remain challenges.

1.5.2. Domestic research status on centrifugal contacting

Centrifugal contacting technology is still new in Vietnam, with very limited research. The Institute of Energy and Environmental Technology has begun exploring the technology and has some experience applying it to process enhancement, specifically for biogas purification and ammonium removal from wastewater.

1.5.3. Necessity of research implementation

Given the advantages of HiGee technology for wastewater treatment demonstrated in developed countries, along with existing challenges in treating high-strength ammonium landfill leachate in Vietnam, testing HP_2R equipment for ammonium stripping as an alternative to conventional packed towers could not only overcome current limitations—such as reducing load, equipment size, and retention time, while increasing treatment capacity and lowering capital costs—but also serve as a foundation for broader application of HP_2R in ammonium and other volatile contaminant removal from wastewater.

CHAPTER 2. MATERIALS AND METHODS

2.1. Research objects

2.1.1. HP2R equipment

The primary object of this study is the high-performance rotating reactor (HP2R) developed by the Institute of Science and Technology for Energy and Environment.

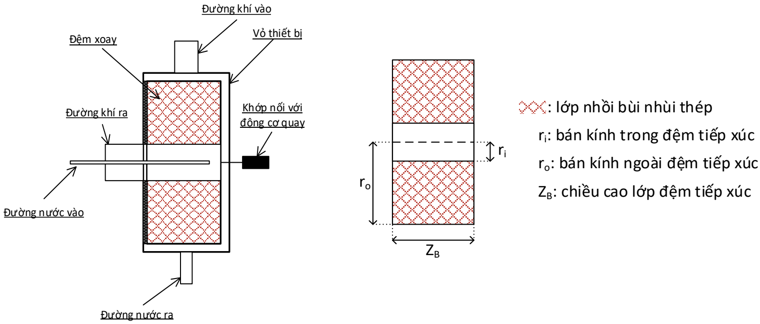


Figure 2.1. Structure of the HP2R device

2.1.2 Wastewater

a. Synthetic wastewater: NH_4Cl (Merck, Germany) dissolved in deionized water to achieve a fixed concentration of 1000 ± 50 mg/L.

b. Livestock wastewater: collected from a household-scale pig farm in Vĩnh Tường commune, Vĩnh Phúc province.

c. Landfill leacha te: Leachate was collected from the Nam Sơn landfill (Sóc Sơn district, Hanoi).

2.1.3. Chemicals and equipment: Chemicals, instruments, and equipment from the laboratory of the Institute of Energy and Environmental Science and Technology.

2.2. Research methods

2.2.1. Experimental methods

A detailed flow chart of the experimental procedure is shown in Figure 2.2.

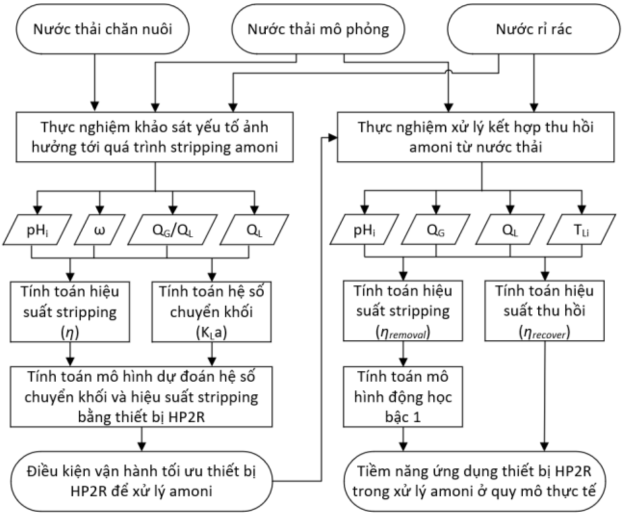


Figure 2.2. Block diagram of the research sequence for high-ammonia wastewater treatment using the HP2R device

2.2.2. Analytical methods

• **NH_3-N concentration:** using an ammonia ion-selective electrode method (TCVN 7872:2008).

• **pH:** using HI1131B electrode (Hanna, USA).

• **Temperature:** using HI 7662-T temperature probe (Hanna, USA).

2.2.3. Calculation method

Appropriate calculation methods were applied to determine stripping efficiency (η), overall liquid-phase mass transfer coefficient (K_La), ammonia recovery efficiency ($\eta_{recover}$), etc.

2.2.4. Data treatment

C All experimental results were performed in triplicate (n = 3). Data were processed using functions in Microsoft Excel.

CHAPTER 3. RESULTS AND DISCUSSIONS

3.1. Results of investigating factors affecting ammonia stripping using the HP2R device

3.1.1. Results of ammonia stripping using the HP2R device with simulated wastewater

The results showed that pH above 10 significantly increased ammonia removal efficiency. Increasing rotational speed (ω = 900–1200 rpm) and the Q_G/Q_L both improved efficiency, with higher rotational speeds notably enhancing the overall volumetric mass transfer coefficient (K_La). Additional stripping cycle could raise the total removal efficiency to 83.0–92.69% (corresponding to a decrease in NH_3-N concentration from 1000 ppm to 162–73.1 ppm)

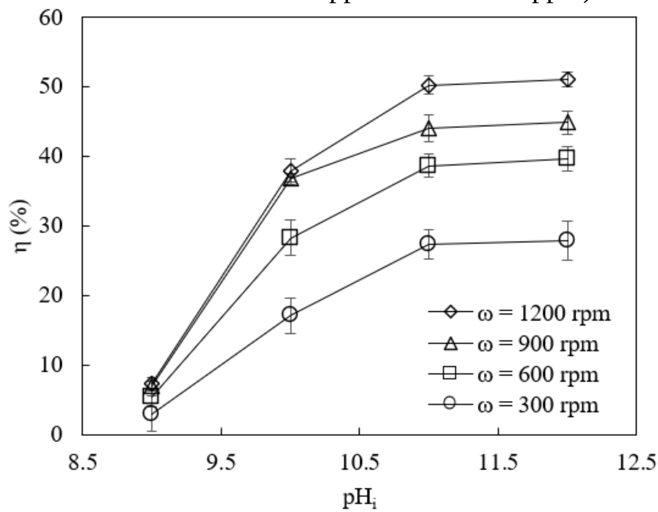


Figure 3.1 Effect of pH on NH_3-N removal efficiency at a gas-to-liquid flow ratio (Q_G/Q_L) of 850

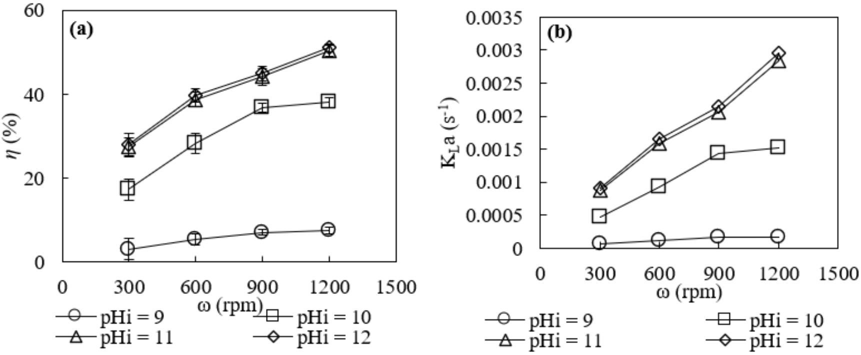


Figure 3.2. Effect of rotational speed on (a) NH_3-N removal efficiency and (b) K_La

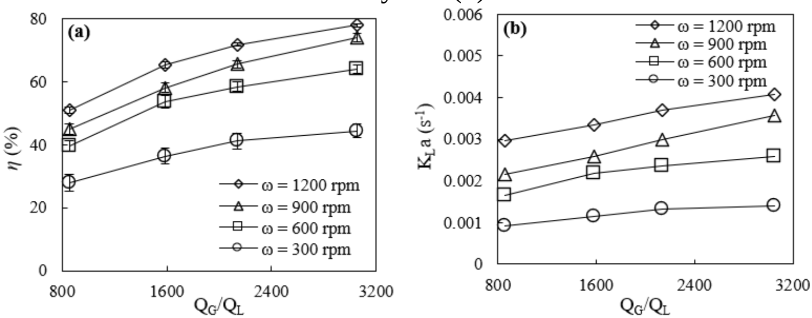


Figure 3.3. Effect of Q_G/Q_L on (a) NH3-N removal efficiency and (b) K_La

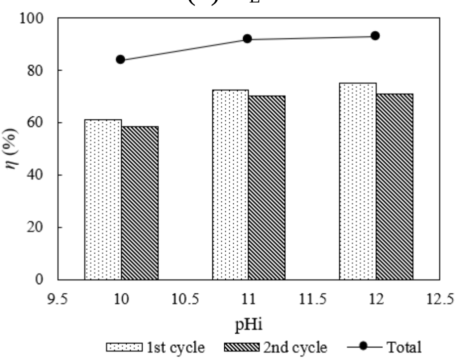


Figure 3.4. Ammonia stripping results in cyclic operation at Q_G/Q_L = 3054, ω = 900 rpm, and C_{Li} = 1000 mg/L

3.1.2. Ammonia stripping results using the HP2R device with livestock wastewater

The stripping efficiency (η) ranged from 33–78% at pH_i = 11 and a rotational speed of 900–1200 rpm. The volumetric mass transfer coefficient (K_La) reached 5.04–13.68 h^{-1}, higher than that of conventional packed towers (1.2 h^{-1}) and heated spray systems (0.297 h^{-1}). At high pH, carbonate salts and co-precipitated solids were observed, posing a clogging risk; however, the system could easily remove these deposits when operating at rotational speeds above 900 rpm.

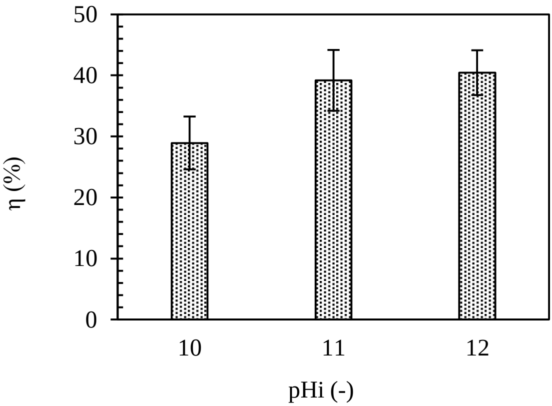


Figure 3.5. Effect of initial pH on ammonia stripping efficiency from livestock wastewater

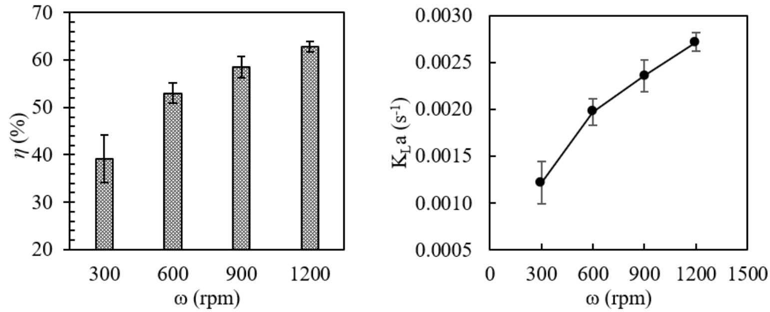


Figure 3.6. Effect of ω on η and K_La on NH_3 stripping from livestock wastewater

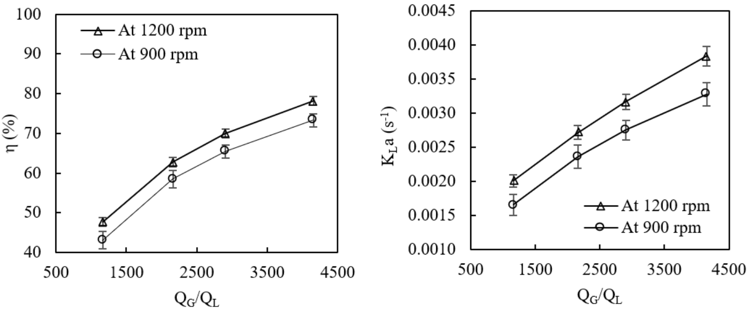


Figure 3.7. Effect of Q_G/Q_L on η and K_La on NH_3 stripping from livestock wastewater

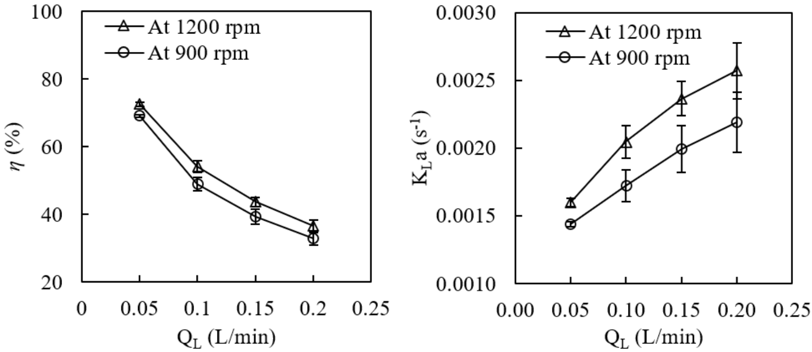


Figure 3.8. Effect of Q_L on η and K_La on NH_3 stripping from livestock wastewater

3.1.3. Results of ammonia stripping using the HP2R device with landfill leachate

Under operating conditions of pH_i 9.5–11.5, Q_G = 76–272 L/min, Q_L = 0.05–0.20 L/min, ω = 300–1200 rpm at 30 °C, the stripping efficiency (η) ranged from 17.1–71.8%, with K_La values of 0.0005–0.0039 s^{-1}. Multiple stripping cycles can increase the total η to 94.6% after five cycles (100 minutes) at pH_i 11.5. A key advantage of HP2R is its ability to maintain high removal efficiency with lower alkali consumption, which can be compensated by increasing the rotational speed or gas flow rate. Multi-cycle stripping operation can further enhance the overall removal efficiency, reaching up to 94.6% after five cycles (100 minutes) at pH_i 11.5. However, strong mechanical vibrations observed at rotational speeds above 1200 rpm will need to be addressed during the design of large-scale HP2R systems.

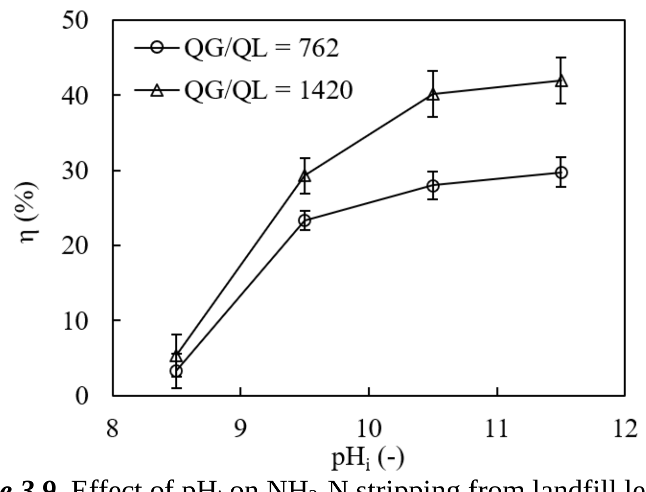


Figure 3.9. Effect of pH_i on NH_3-N stripping from landfill leachate

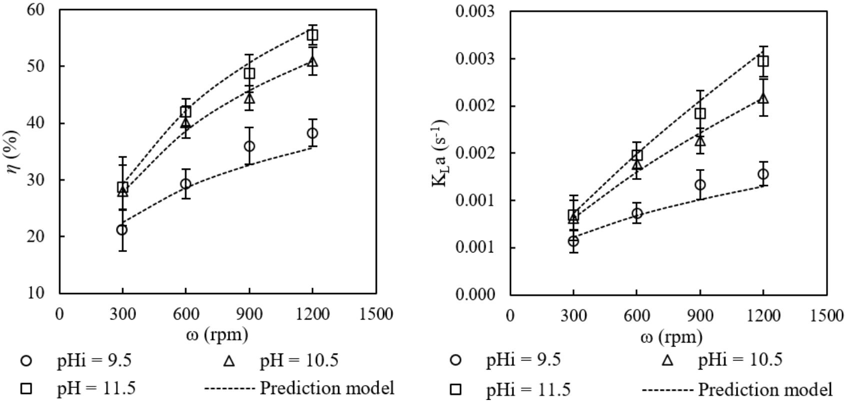


Figure 3.10. Effect off ω on η and K_La of NH_3-N stripping from landfill leachate

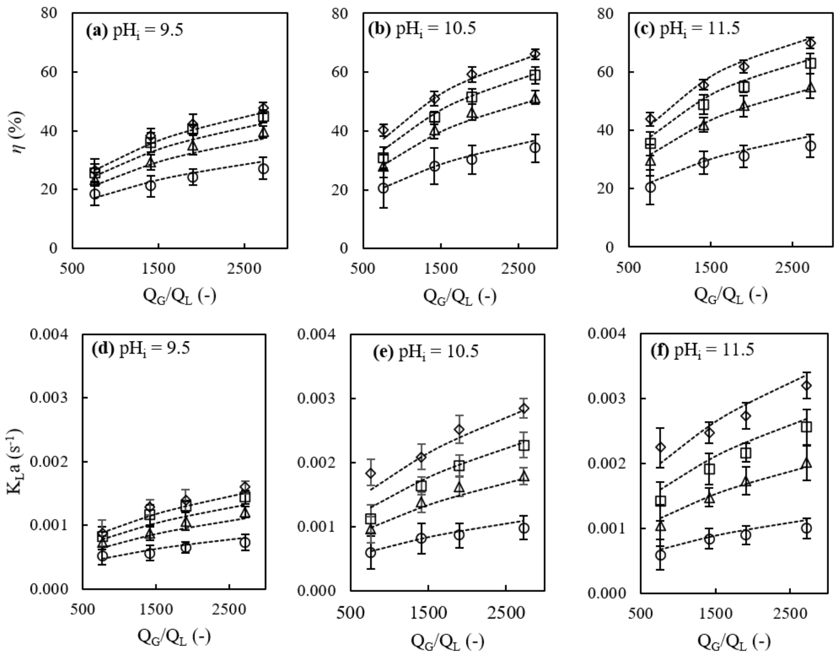


Figure 3.11. Effect of Q_G/Q_L on η and K_La of NH_3-N stripping from landfill leachate

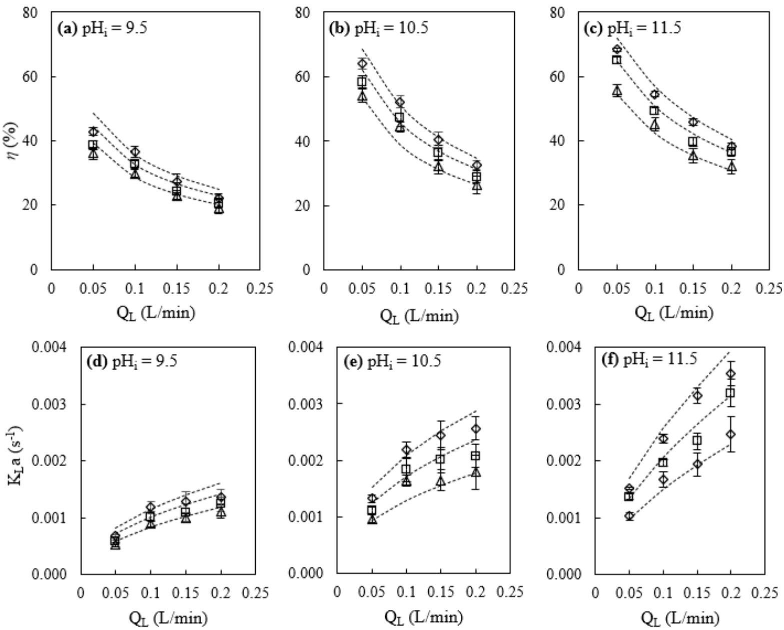


Figure 3.12. Effect of Q_L on η and K_La of NH_3-N stripping from landfill leachate

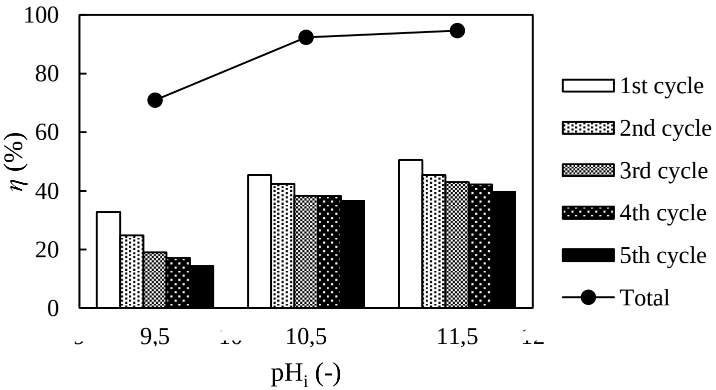


Figure 3.13.Ammonia stripping from landfill leachate results in cyclic operation

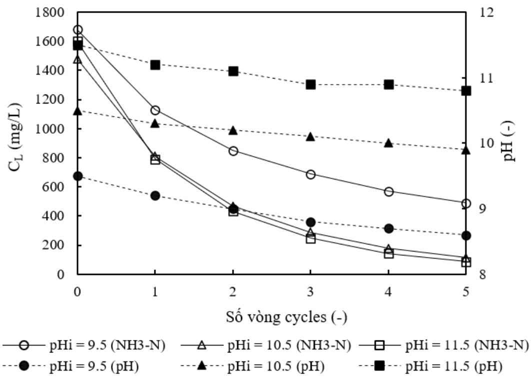


Figure 3.14. Variation of NH_3-N conc. and pH during cyclic operation of NH_3-N stripping from landfill leachate

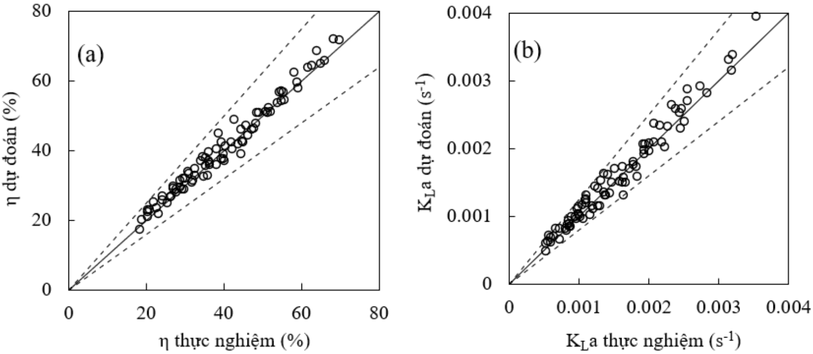


Figure 3.15. Comparison between practical and empirical data of η (a) and K_La (b) of NH_3-N stripping from leachate

3.2. Results of combined ammonia removal and recovery experiments using the HP2R device from wastewater

3.2.1. Results of combined ammonia removal and recovery from synthetic wastewater using the HP2R device

Increasing liquid flow rate from 0.05 to 0.20 L/min raised removal efficiency from 75% to 89.8%, but recovery efficiency gradually decreased (74.6% - 69.2%).

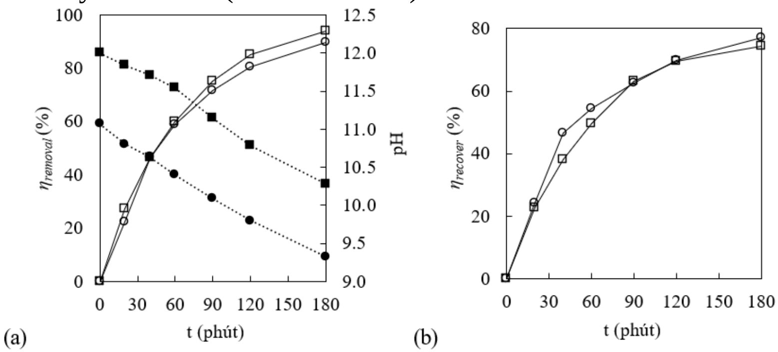


Figure 3.16. Ammonia stripping (a) and recovery (b) from synthetic wastewater using HP2R under various pH

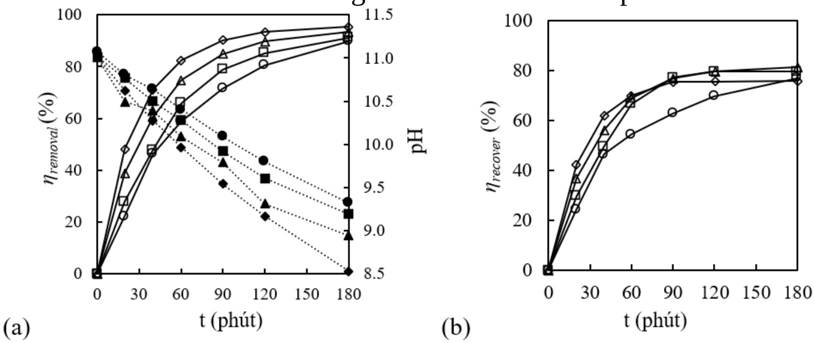


Figure 3.17. Ammonia stripping (a) and recovery (b) from synthetic wastewater using HP2R under various Q_G

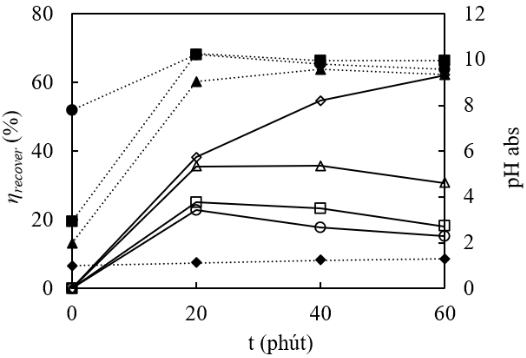


Figure 3.18. Effect of absorbent pH on ammonia recovery

3.2.2. Results of combined ammonia removal and recovery from landfill leachate

Ammonia recovery efficiency using a single absorption unit ranged from 67.1% to 84.8% and was mainly influenced by the ammonia concentration in the gas phase, which depended on Q_G and Q_L. The optimal operating conditions to achieve 95% removal efficiency and 80% recovery efficiency were: Q_G = 200 L/min, Q_L = 0.2 L/min, rotational speed of 900 rpm, and T_{Li} between 30–40 °C. The recovered solution reached high ammonia concentrations (1930–3360 mg/L).

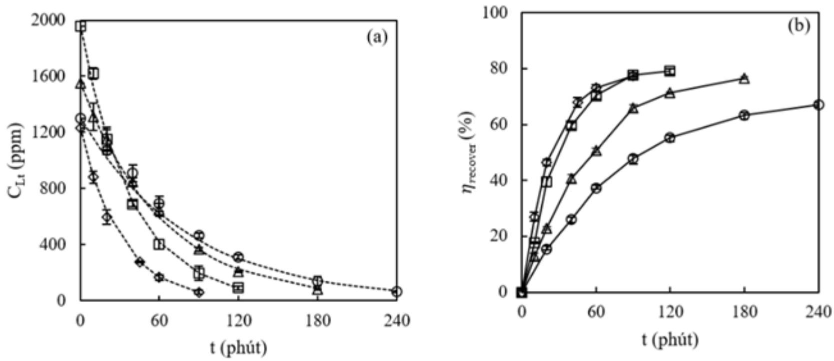
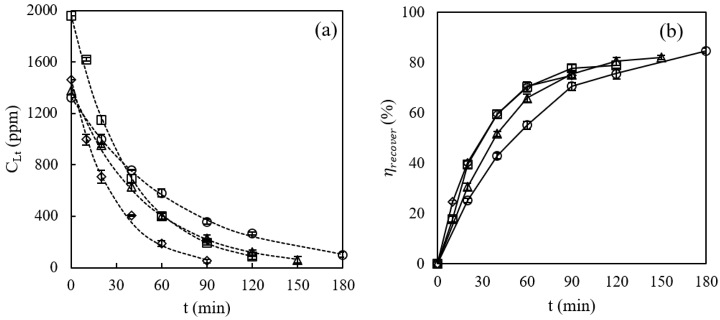
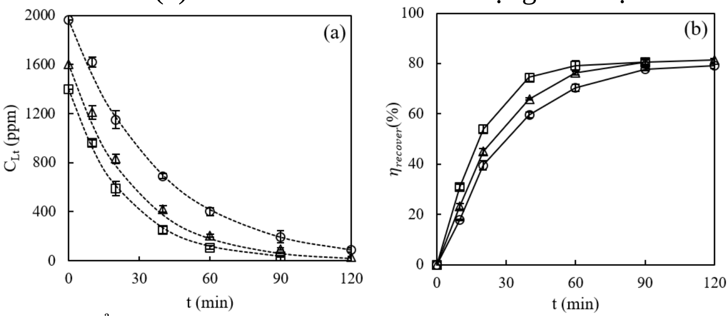


Figure 3.19. Effect of Q_G on ammonia removal (a) and recovery (b) from landfill leachate using HP2R



Hình 3.20. Ảnh hưởng của lưu lượng nước thải tới hiệu quả xử lý (a) và thu hồi (b) amoni từ nước rỉ rác sử dụng thiết bị HP2R

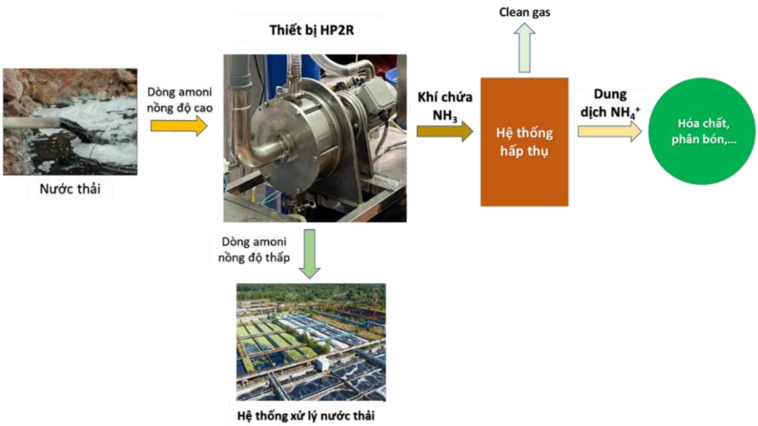


Hình 3.21. Ảnh hưởng của nhiệt độ nước thải tới hiệu quả xử lý (a) và thu hồi (b) amoni từ nước rỉ rác sử dụng thiết bị HP2R

3.3. Proposed model for potential application of centrifugal contact principle in large-scale ammonia removal and recovery

3.3.1. Technical–economic assessment for the ammonia stripping and recovery process using HP2R at a capacity of 150 m³/day.

The treatment cost for ammonia in 1 m^3 of wastewater with an ammonia concentration of 1000 mg/L is VND 22,000/m^3 (using NaOH) and VND 21,500/m^3 (using $Ca(OH)_2$).



Hình 3. 22. Hướng ứng dụng thiết bị HP2R ở quy mô thực tế

CONCLUSION AND RECOMMENDATIONS

Conclusion

The study demonstrated the potential of the High-Performance Rotating Packed Bed (HP2R) in ammonia stripping technology for treating and recovering ammonia from synthetic wastewater, swine farm effluent, and landfill leachate. Key findings include:

- pH $\geq$ 11 promotes formation of NH_3, enhancing stripping efficiency;
- High rotational speed (ω) significantly boost the overall mass transfer coefficient (K_La);
- Increasing the Q_G/Q_L ratio improves efficiency, though ω has a greater effect;
- Higher Q_L reduces per-cycle efficiency but shortens treatment time in recirculation mode;
- Elevated temperature promotes NH_3 volatilization but requires control to prevent heat loss;
- HP2R achieved $\eta_{removal} \geq 95\%$, $K_La = 0.7–2.5\ h^{-1}$, and ηrecover = 67–85% within 1.5–2 hours for wastewater with >1000 mg/L NH_3-N;
- Preliminary assessment at a 150 m^3/day scale indicates high economic, environmental, and sustainability benefits.

Recommendations

- Apply CFD modeling to optimize rotor and packing design; conduct pilot and full-scale trials in Vietnam with various wastewater types; integrate HP2R with other technologies to maximize efficiency and reduce costs;
- Develop anti-fouling solutions and assess the impact of co-stripping VOCs to ensure ammonia recovery purity.

NOVEL CONTRIBUTION OF THE RESEARCH

- The thesis comprehensively surveyed the influencing factors and operating conditions of the HP2R device on the NH3-N stripping efficiency and the overall mass transfer coefficient KLa of the process for three wastewater objects.
- HP2R device has improved the treatment efficiency and maximum recovery to 95% and 85% respectively, especially with high ammonium concentrations in wastewater ranging from 2000 to more than 3000 mg/L.

RELATED PUBLICATIONS

*** Main author:**

1. **Viet M. Trinh**, Thao Phuong Nguyen, Tung Huu Pham, Hieu Minh Trinh, Minh Tuan Nguyen, Manh Van Do, Long Thanh Ngo, Tuyen Van Trinh, Intensified ammonia stripping from landfill leachate using a high-performance rotating reactor, Journal of Environmental Chemical Engineering, Volume 11, Issue 5, 2023, 110416, ISSN 2213-3437,

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