Vietnam Journal of Science and Technology ***62*** *(4) (2024) 775-786*

doi:10.15625/2525-2518/18070

Ammonia removal from digested swine wastewater using a high-performance rotating reactor

Viet M. Trinh[1, 2], Van Tuyen Trinh[1, *], Phuong Thao Nguyen[1], Huu Tung Pham[1], Tuan Minh Nguyen[1], Van Manh Do[1], Thanh Long Ngo[3]

[1]*Institute of Environmental Technology, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Cau Giay, Ha Noi, Viet Nam*

[2]*Graduate University of Science and Technology, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Cau Giay, Ha Noi, Viet Nam*

[3]*Hanoi University of Civil Engineering, 55 Giai Phong, Hai Ba Trung, Ha Noi, Viet Nam*

[*]Emails: *trvtuyen@gmail.com*

Received: 8 February 2023; Accepted for publication: 27 March 2023

Abstract. The livestock industry generates significant wastewater pollution, challenging agricultural sustainability. Even with anaerobic digestion, digested wastewater often exceeds discharge standards due to high ammonia content, resulting in a low C/N ratio that inhibits aerobic biological treatment. Therefore, pretreatment to reduce ammonia is necessary. The High-Performance Rotating Reactor (HP2R) has shown promise in removing high ammonia concentrations from synthetic wastewater via stripping. This study examined HP2R's effectiveness on digested swine wastewater under various conditions, assessing the impact of pre-alkalinization (pH_i), rotating speed (ω), gas flow rate (Q_G), and wastewater flow rate (Q_L) on ammonia removal efficiency (ARE) and the overall liquid mass transfer coefficient (K_La). Results indicated HP2R could effectively remove ammonia in a laboratory-scale batch mode, with ARE ranging from 33 % to 78 % under different conditions. The K_La values ($0.0014\ s^{-1}$ to $0.0038\ s^{-1}$) showed improved mass transfer compared to conventional packed columns.

Keywords: air stripping, ammonia, swine wastewater, HP2R

Classification numbers: 3.4.2, 3.7.1, 3.7.4.

1. INTRODUCTION

In Vietnam, the livestock industry vastly contributes to agricultural production, accounting for 25.2 % of the sector's GDP with a steady growth of 4-6 % per year [1]. This results in massive waste generation, with around 80 million tons of animal waste annually in 2015 [2]. Swine farms discharge about 5.6 million m^3 of wastewater per day, comparable to cow and buffalo farming [3]. Swine wastewater, consisting of pig urine, manure, leftover food, sediment, and washing water [4], contains high levels of organic substances, nitrogen, phosphorus, and residual antibiotics [5]. Anaerobic digestion, used by 59.7 % of swine farms, is the primary treatment method [6]. However, the digested wastewater still has high nitrogen content (TN >

400 mg/L) [7], leading to eutrophication and hindering aerobic biological processes due to its low C/N ratio [8].

Regarding digested swine wastewater, the nitrogen content is mostly in the form of ammonia-nitrogen or ammonium due to the decomposition of amines with the absence of oxygen during the anaerobic digestion process [9]. There are several physical/chemical approaches to ammonia removal such as chemical precipitation, ammonia stripping, ion exchange, adsorption, and membrane filtration [10 - 12]. However, for the ammonia removal and recovery for the upstream influent like digested swine wastewater, ammonia stripping is the most available and popular on the market [13]. Air stripping is a less chemical-intensive and commonly used process for ammonia removal from wastewater, relying on the conversion of ammonium ions to ammonia at high pH (above 10), which is then stripped to the gas phase [10, 14]. The most common equipment for this is the packed column, which enhances the contact surface area using objects like Raschig rings or wire mesh [15]. This method has been successful in removing and recovering ammonia from concentrated wastewater streams such as landfill leachate [16, 17], pig slurry [18], and anaerobic digestion [19]. For example, ammonia removal from landfill leachate (2000 mg/L) reached 98 % in 4-9 days using a pilot-scale column packed with Raschig rings at pH 12.1 [16]. However, packed columns have a major drawback: higher gas-to-liquid flow rate ratios increase the risk of flooding due to pressure drop and liquid hold-up, requiring higher investment costs and larger space [10, 13]. This risk is exacerbated by carbonate deposition and high liquid feeding [20, 21].

A novel design to improve ammonia stripping and reduce equipment size is the rotating packed bed (RPB) [22]. This compact design offers high mass transfer and shortened liquid retention time, benefiting applications like VOCs stripping [23], CO2 absorption [24], ClO2 generation [25], and ammonia removal [14, 26, 27]. Yuan et al. demonstrated that RPBs have a significantly higher mass transfer rate (K_La 12.3-18.1 h^{-1}) compared to conventional stripping columns (KLa 3.5-9 h^{-1}), achieving ammonia removal efficiencies of 60-95% at pH 11 and an initial concentration of 1000 mg/L [26]. However, horizontal RPB designs encountered slow liquid exit and bed clogging [28]. Solutions include a steep casing bottom or higher casing height. The High-Performance Rotating Reactor (HP2R) with a vertical bed design avoids these issues [14]. HP2R's horizontal bed design offers stability at high speeds, easy mobilization, less space usage, and resistance to clogging and flooding without a large, sloping casing bottom. Experiments achieved significant ammonia removal efficiency (83-93 %) with a double cycle of stripping at pH 10-12.

These findings show that the HP2R has high potential as an alternative to packed columns for ammonia removal from wastewater. While various parameters affecting ammonia removal efficiency have been studied, the application to real wastewater remains unclear due to a lack of studies and the challenge of high suspended solids causing fouling [29]. This study focused on the ammonia removal efficiency of HP2R from digested swine wastewater under different conditions. The effects of pre-alkalinization (pH_i 10 - 12), rotating speed (ω 900 - 1200 rpm), gas flow rate (Q_G 116 - 415 L/min), and wastewater flow rate (Q_L 0.05 - 0.20 L/min) on ammonia removal efficiency and the overall liquid mass transfer coefficient (K_La) were evaluated. This study also compared ammonia stripping between swine and synthetic wastewater to assess the impact of suspended solids. The results provide fundamental information for future applications of HP2R in ammonia removal and recovery from swine wastewater.

2. MATERIALS AND METHODS

2.1. Digested swine wastewater characteristic

Digested swine wastewater was collected from a household swine farm in Vinh Tuong commune, Vinh Phuc province, Vietnam. Samples were taken from the farm's anaerobic tank discharge and stored in 20-L plastic containers, then transferred to the Institute of Environmental Technology's laboratory. Containers were refrigerated at 4 °C to preserve the wastewater's characteristics. Experiments were conducted the day after collection to avoid any variations. The total nitrogen (TN) exceeded Vietnam's National Technical Regulation (QCVN 62:2016/BTNMT Standard A) [30]. The wastewater's TN, mainly ammonia (NH_3-N) at 657 mg/L (> 99 % of TN), is suitable for air stripping. Original characteristics are detailed in Table 1.

Table 1. Characteristic of the digested swine wastewater and the comparison with the discharge standard.

Parameters	Unit	Digested swine	QCVN 62:2016/BTNMT Standard A [30]
pH	-	7.5 ± 1.0	6 – 9
Biological oxygen demand - BOD_5	mg/L	430 ± 95	40
Chemical oxygen demand - COD	mg/L	1120 ± 182	100
Total suspended solids - TSS	mg/L	143 ± 23	50
Total nitrogen - TN	mg/L	660 ± 93	50
Ammonia nitrogen - NH_3-N	mg/L	657 ± 101	-

2.2. HP2R equipment characteristics and experimental procedures

In this study, ammonia removal was performed using HP2R equipment previously used for simulated wastewater [14]. The packed bed volume (V_B) is 7.74×10^{-4} m³, with a bed height (Z_B) of 0.039 m, inner radius (r_i) of 0.024 m, and outer radius (r_o) of 0.083 m (Figure 1a and Table 2). A diaphragm pump (EHN-C36VH4R, Iwaki, Japan) ensured stable liquid feeding, while an air blower (TJ-750, Tongjin, China) with variable frequency control adjusted air feeding. An anemometer (Kestrel 5500, Kestrel, USA) monitored the air velocity in the outlet pipe.

Table 2. Characteristic of the packed bed of the HP2R equipment.

Parameters	Unit	Characteristic
Packed bed inner radius (r_i)	m	0.024
Packed bed outer radius (r_o)	m	0.083
Packed bed average radius (r_{avg})	m	0.054
Packed bed axial height (Z_B)	m	0.039
Packed bed volume (V_B)	m^3	7.74×10^{-4}
Packing material	-	Stainless-steel wire mesh

Figure 1b presents the experiment on ammonia-nitrogen removal from digested swine wastewater using HP2R equipment. The experiments varied conditions of pH (pH_i 10-12), rotational speed (ω 300 - 1200 rpm), gas flow rate (Q_G 116 - 415 L/min), and liquid flow rate (Q_L 0.05 - 0.2 L/min) at a controlled temperature of 30 ± 1 °C. Pre-alkalinization was achieved by adding solid NaOH. The HP2R was set to stable rotational speed and gas flow rate. After reaching the desired pH, the alkalinized wastewater was continuously fed to the HP2R at a constant rate. The output air was captured to prevent ammonia emission, and wastewater samples were collected after 10 minutes of operation. Each sample was collected in triplicate, stored in sealed beakers, and analyzed immediately to prevent ammonia evaporation. Data was analyzed and plotted using MS Excel.

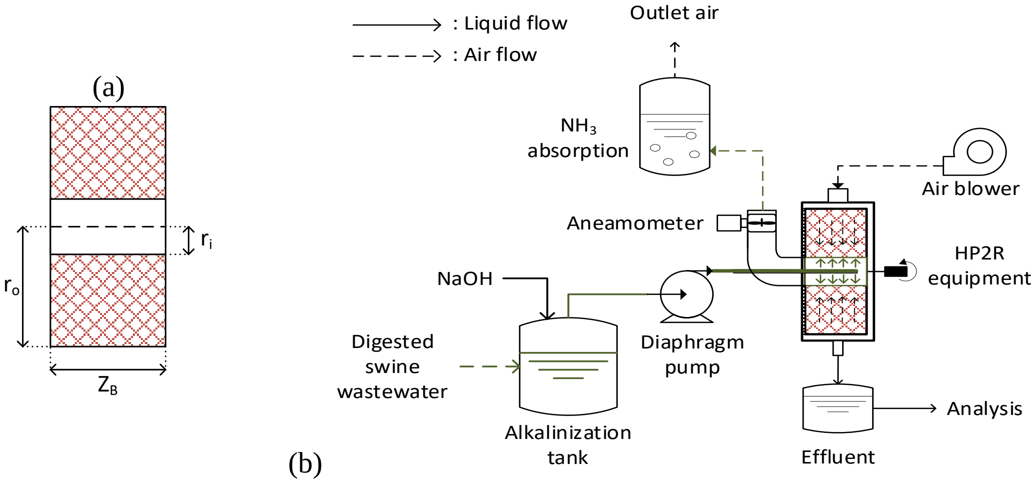

Figure 1. The basic design parameters of the packed bed (a) and a schematic diagram of ammonia stripping (b) from digested swine wastewater using HP2R equipment.

2.3. Ammonia analysis and theoretical calculation

The ammonia concentration in the liquid samples was measured by the ammonia-selective electrode method [31] using the HI 4101 ammonia-selective electrode (HI 4101, Hanna, USA) and read by read and displayed by the pH/ISE/mV meter (HI 5222, Hanna, USA). The ammonia removal efficiency (ARE) was calculated based on the change in ammonia concentration of the swine wastewater samples as follows:

$$\boldsymbol{ARE}\ (\%) = \frac{\boldsymbol{C_{Li}} - \boldsymbol{C_{Lo}}}{\boldsymbol{C_{Li}}} \times \mathbf{100}\% \tag{1}$$

where the C_{Li} and C_{Lo} are the input and output concentrations, respectively, of ammonia concentration.

In this study, the mass-balance concept and the two-film theory were employed for the computation of the overall-liquid volumetric mass transfer coefficient (K_La). The K_La (relative to the unit liquid volume) is the common characteristic to be considered in design, scale-up, and optimization of gas-liquid contactors like stripping columns [32]. In this study, the K_La was calculated to understand the overall transfer rate of ammonia from the liquid phase into the gas phase per unit of time. This computation was proposed to determine the mass transfer of centrifugal vapor-liquid contacted by Chen *et al.* [33, 34]. The calculation of K_La was derived from the differential volume with the cross-sectional area and the thickness of the thin film with the assumption of the neglection of gas-side mass transfer resistance. The expression for K_La calculation is presented as follows [33]:

$$K_La = \frac{Q_L}{V_B} \frac{ln\left[\left(1-\frac{1}{S}\right)\frac{C_{Li}}{C_{Lo}} + \frac{1}{S}\right]}{1-\frac{1}{S}} \tag{2}$$

where Q_L is the swine wastewater flow rate (m^3/s), V_B is the volume of the packed bed (m^3), and S is the stripping factor which is defined as follows [33]:

$$S = H_C \frac{Q_G}{Q_L} \quad (3)$$

where H_C (0.000824) is the dimensionless Henry's law constant of ammonia at 30 ^oC according to the NIST Chemistry Webbook [35], Q_G is the gas flow rate of the system.

3. RESULTS AND DISCUSSION

3.1. Effect of pre-alkalinization (pH_i) of digested swine wastewater on the ARE

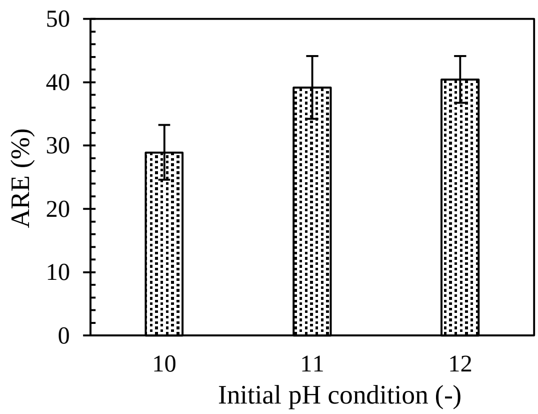

Figure 2. The effect of digested swine wastewater pre-alkalinization on the ammonia removal efficiency (Q_G = 216 L/min, Q_L = 0.10 L/min, ω = 300 rpm, C_{Li} = 657 mg/L).

The effect of pH_i on ammonia removal from digested swine wastewater using the HP2R equipment is presented in Figure 2. The operational conditions were kept constant at Q_G of 216 L/min, Q_L of 0.10 L/min, ω of 300 rpm, while the pH varied from 10 to 12. The higher pH_i might exhibit higher ARE, while it could trigger the clogging phenomenon inside the packing and liquid output. The pH_i of digested swine wastewater had a significant effect on the ARE since it influences the ammonia species distribution. The ARE increased from 28.92 % to 39.18 % when the initial pH condition was raised from 10 to 11. This result was even higher than that of the ammonia stripping from synthetic wastewater (17.20 % to 27.40 %) in the previous study at a similar rotating speed of 300 rpm [14]. This could be explained by the higher Q_G (216 L/min) in this study than the Q_G (85 L/min) of the synthetic wastewater experiment. According to the species distribution diagram of ammonia by Jiang *et al*., the proportion of NH_3 in the solution increases from 40 % at pH 9 to 80 % at pH 10, consequently to almost 100 % at pH 11 [36]. The proportion of NH_3, however, remains almost unchanged between pH 11 and 12. That explained the negligible difference between ARE at pH 11 (39.18 %) and pH 12 (40.45 %). The pH_i above 11 was also a preference for ammonia stripping conditions in previous studies using packed columns [16, 18]. Bonmati and Flotats recorded a significant improvement in ammonia removal when the alkalinization of pig slurry was conducted to pH 11 compared to the raw sample [18]. Regarding the swine wastewater in this study, the sight of precipitated solid in the output sample was detected at high initial pH_i of 11 and 12 which was absent in the synthetic ammonia water in the previous study [14]. This could be the result of the carbonate salts of metal from swine wastewater and partial co-precipitation of suspended solids after pre-alkalinization.

3.2. Effect of rotational speed (ω) on the ARE and K_La

The effect of the rotational speed on the ARE and the K_La from digested swine wastewater using the HP2R equipment is shown in Figure 3. In this experiment, the alkalinization was selected at pH_i of 11, while other parameters were kept constant at Q_G of 216 L/min, Q_L of 0.10 L/min. The K_La of ammonia stripping was calculated to investigate its trend under the variation of rotating speed since it has been reported that higher centrifugal force contributed to intensified mass transfer in the rotating packed bed [33]. The ammonia removal from digested swine wastewater drastically increased as the rotating speed went faster. The ARE significantly rose from 39.18 % to 53.02 % as ω changed from 300 rpm to 600 rpm. The ARE value continued to increase but at a slower pace to 58.45 % and 62.77 % at ω of 900 rpm and 1200 rpm, respectively. Regarding the conventional packed column, the ammonia removal efficiency from wastewater could only be improved by the increment of the gas-to-liquid flow rate ratio. It could be done by either increasing the gas feed to the column or expanding the circulation time (longer hydraulic retention time) of the wastewater [17]. However, the novel advance of the HP2R equipment is that the ARE could also be significantly improved by accelerating the rotational speed [14]. It was the result of intensified mass transfer, particularly from 0.0012 s^{-1} to 0.0027 s^{-1} as the ω increased from 300 to 1200 rpm, respectively, in the ammonia removal from digested swine wastewater. This indicated that the K_La of ammonia stripping from swine wastewater with higher TSS content was similar to the result of synthetic ammonia-contained water (K_La of 0.0009 s^{-1} to 0.0028 s^{-1}) [14]. At higher rotating speeds, the collision between liquid and contact media under large centrifugal acceleration created special flow patterns of the liquid [37]. At ω from 900 to 1200 rpm, the flow pattern shifted from droplet form into thin-film form which enhanced the surface area of liquid to contact with the gas flow. This effect was also recorded in the stripping of ammonia in the synthetic wastewater which was reported by Yuan *et al*. [26, 27].

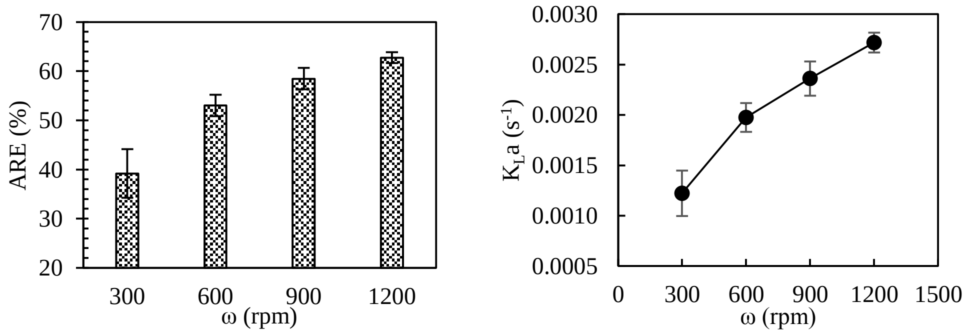

Figure 3. The effect of ω of HP2R on the ammonia removal and the overall liquid-phase mass transfer coefficient (K_La) from digested swine (Q_G = 216 L/min, Q_L = 0.10 L/min, pH_i = 11, C_{Li} = 657 mg/L).

Another benefit of operating at a higher rotating speed was more stability and even distribution of the wastewater inside the packing. This benefit was indicated in the decrease of the standard deviation in both the ARE and the K_La results (Figure 3). Moreover, the precipitated solid found in the output sample was denser at the ω of 900 – 1200 rpm compared to that of ω of 300 rpm. This finding showed that a higher rotating speed was capable to discard the solid contents of the wastewater away from the packing which consequently avoided possible clogging or fouling during operation. Despite having higher ARE and mass transfer, the decision on selecting the optimal rotating speed should be carefully considered since a higher rotating speed means higher energy consumption and the overheating problem of the rotor shaft [14].

3.3. Effect of gas flow rate (Q_G) on the ARE and K_La

The effect of Q_G on the ammonia removal and the K_La from digested swine is presented in Figure 4. The results indicated that increasing the fresh air loading to the system enhanced the ARE and the K_La of ammonia removal from digested swine wastewater of HP2R at both rotating speed stages. The ARE significantly increased from around 45 % to 75 % as the Q_G increased from 116 L/min to 415 L/min. Similar to the ARE, the enhancement in the mass transfer of ammonia removal from digested swine wastewater was also recorded as the K_La nearly doubled from 0.0020 s^{-1} to 0.0038 s^{-1}. The improvement of ARE and K_La between ω of 900 rpm and 1200 rpm was insignificant by 4 - 6 % and 0.0003 to 0.0005 s^{-1}, respectively. The comparable effect of Q_G on the ARE from landfill leachate was recorded in the results of Ferraz *et al*. [17]. The authors reported that the Q_G of 4500 L/h derived almost 99 % of ARE after 24 h with the K_La of 0.18 h^{-1} while it took 12 days to achieve a similar ARE with only 0.0154 h^{-1} of K_La. In comparison with the ammonia stripping from synthetic ammonia-contained wastewater, the K_La of 0.0032 s^{-1} was achieved at a higher gas-to-liquid ratio (Q_G/Q_L = 2910) compared to the result of Yuan *et al*. [26] using the horizontal-bed equipment (Q_G/Q_L = 1600) and Viet *et al*. [14] using the same equipment (Q_G/Q_L = 1600). The higher solid content of swine wastewater compared to the synthetic sample might require a larger dosage of fresh air to achieve similar K_La since it might partially accumulate the contact area of gas and liquid phases.

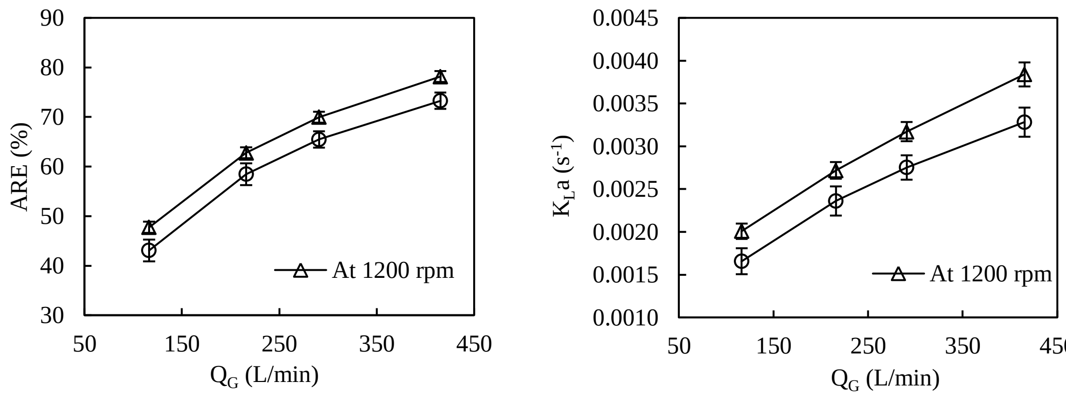

Figure 4. The effect of Q_G on the ammonia removal and the overall liquid-phase mass transfer coefficient (K_La) from digested swine (Q_L = 0.10 L/min, pH_i = 11, ω = 900 rpm and 1200 rpm, C_{Li} = 657 mg/L).

In this study, the ARE of 73.29 % and K_La of 0.0033 s^{-1} were achieved at Q_G of 415 L/min, equivalent to Q_G/Q_L of 4150, which was much greater than the maximum ratio of the conventional packed column in previous studies with swine wastewater (from 45 to 400) [16, 17]. In a design process of a conventional packed column, the Q_G/Q_L is normally limited due to the pressure drop and the flooding point of liquid [38]. The flooding phenomenon often occurs when the liquid downward flow is blocked by the excessive load of gas and remains bubbled in the top surface of the packed column. Therefore, despite the enhanced ARE and K_La, the Q_G/Q_L in the conventional column is normally limited (around 400) to avoid such column fouling. The HP2R, on the other hand, could be operated in a much larger Q_G/Q_L ratio (over 4000) with the high centrifugal field generated by the accelerated rotating bed, resulting in higher ARE and K_La without encountering the flooding and fouling of the system. However, an adequate gas flow rate should be carefully selected for HP2R to avoid the turbulence of the absorption unit.

3.4. Effect of wastewater flow rate (Q_L) on the ARE and K_La

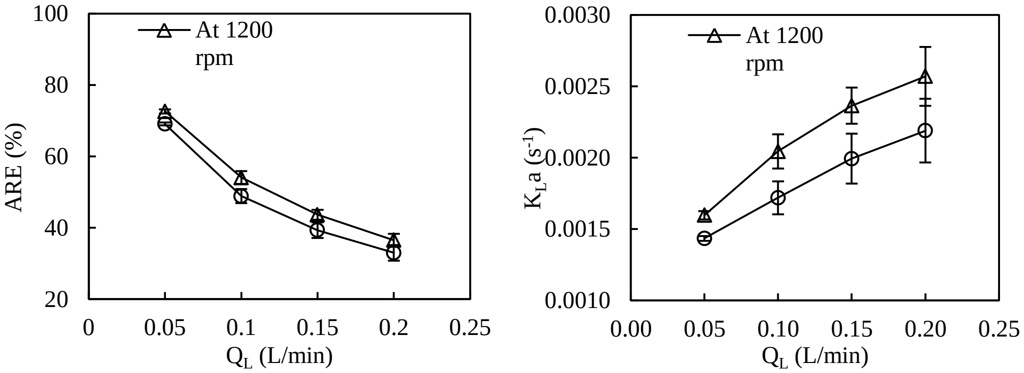

Figure 5. The effect of Q_L on the ammonia removal and the overall liquid-phase mass transfer coefficient (K_La) from digested swine (Q_G = 216 L/min, pH_i = 11, ω = 900 rpm and 1200 rpm, C_{Li} = 657 mg/L).

The effect of Q_L on the ammonia removal and the K_La from digested swine is presented in Figure 5. In this experiment, the Q_G of 216 L/min instead of 415 L/min was selected to avoid the turbulence of the absorption unit during the experiment. The results indicated that both ARE and K_La significantly depended on the variation of Q_L from 0.05 to 0.20 L/min, but it was an opposite trend. Regarding the ARE, the higher feeding rate of swine wastewater from 0.05 L/min to 0.20 L/min reduced by two folds from approximately 70 to 35 % at both ω of 900 and 1200 rpm. The higher Q_L led to significant loading of wastewater and also reduced the Q_G/Q_L ratio which resulted in lower ARE. Viet *et al*. discussed that a higher liquid flow rate may cause the disturbance of liquid flow leading to an unstable ClO_2 stripping process [25]. Yuan *et al*. also stated that the compensatory effect of a high liquid flow rate was responsible for the decrease in liquid retention time and stripping factor that consequently reduce the ARE [26]. In contrast, the mass transfer was in an increasing trend at higher Q_L. Specifically, when the Q_L changed from 0.05 to 0.20 L/min, the K_La value drastically increased from 0.0014 s^{-1} to 0.0022 s^{-1} and 0.0016 s^{-1} to 0.0026 s^{-1} at ω of 900 rpm and 1200 rpm, respectively. Although the higher wastewater flow rate might have lower ARE, the actual separation rate of ammonia from the liquid phase over time could be significantly improved as the higher mass of ammonia was transferred into the gas phase.

The opposite trend of ARE and K_La indicated that the selection of operational conditions, especially Q_L, is crucial when it takes to the real application. Besides the ammonia removal efficiency, the higher K_La reflects the shorter recirculation time of wastewater for ammonia removal. Moreover, a higher concentration of ammonia in the gas phase and an adequate gas flow rate may be preferable for the effective recovery unit. The comparison of ammonia removal from swine wastewater is presented in Table 3. These methods include ammonia stripping and struvite precipitation, which are two suitable methods for ammonia removal and recovery from a concentrated stream. At a higher Q_G/Q_L ratio of 4150, the maximum ARE from swine wastewater in this study (73.29 %) was comparable to that of the stripping process from synthetic wastewater [14, 26]. This finding indicated that a higher dosage of fresh air might be necessary for the stripping of ammonia from solid-contaminated wastewater like swine wastewater or even fresh pig slurry. Compared to a conventional packed column, the HP2R equipment possessed considerable K_La (11.88 h^{-1}) which was 10 times higher than that of a much larger column (0.83 h^{-1}) [18]. The obtained results were even higher than the innovative heated spraying system of Cao *et al.* for ammonia removal from swine wastewater (K_La = 0.297 h^{-1}) [39]. The ARE from single batch of stripping using HP2R, however, was lower than that of the struvite electrochemical precipitation method of Huang *et al*. [40]. In further studies and future applications, the ARE by stripping with HP2R could be improved by the elongated HRT with less chemical consumption and easy operation.

Table 3. Comparison of high-concentration ammonia removal methods from swine wastewater and others.

Method	Wastewater type	C_{Li} NH_3-N (mg/L)	Equipment size	Experimental condition				ARE (%)	K_La	Ref.
				HRT (h)	Chemical addition	T_{Li} (°C)	Q_G/Q_L			
Air stripping using HP2R	Digested swine ww.	657 ± 101	d = 16.6 cm Z_B = 3.9 cm V_B = 0.774 L	Instant single batch	NaOH pH = 11	30	4150	73.29	0.0033 s^{-1} 11.88 h^{-1}	This study
	Synthetic ww.	1000 ± 100			NaOH pH = 12		3052	74.9	0.0047 s^{-1}	Viet *et al.* [14]
Horizontal rotating packed bed	Synthetic ww.	1000	V_B = 0.4 L	Instant single batch	NaOH pH = 11	30	1600	69	0.0037 s^{-1}	Yuan *et al*. [26]
Stripping via heated spraying system	Swine ww.	611 ± 8	V_{Tank} = 5 L	264	NaOH pH = 9	55	-	97.11	0.297 h^{-1}	Cao *et al.* [39]
Air stripping in packed column	Fresh swine ww.	3.39 g/kg (Fresh slurry) 3.68 g/kg (Digested slurry)	d = 5 cm h = 97.5 cm V = 1.913 L	4 (circulation mode)	NaOH pH = 12	80	75	98.8% (Fresh slurry) 96% (Digested slurry	1.2 h^{-1} (Fresh slurry) 0.83 h^{-1} (Digested slurry)	Bonmati and Flotats [18]
Struvite electrochemical precipitation	Digested swine ww.	426 ± 21	1L reaction vessel	2	Magnesium plate HCl/NaOH pH = 9	-	-	>90%	-	Huang *et al*. [40]

4. CONCLUSIONS

This study comprehensively investigated ammonia removal from digested swine wastewater using HP2R. The results showed that HP2R effectively removed ammonia in a laboratory-scale batch mode, with ammonia removal efficiency (ARE) ranging from 33 % to 78 % under various gas and liquid flow rates. Pre-alkalinization at pHi 11, rotational speeds (ω) of 900-1200 rpm, and an initial ammonia concentration of 660 mg/L enhanced the mass transfer rate (K_La = 0.0014-0.0038 s^{-1}). This performance surpassed conventional packed columns (K_La = 1.2 h^{-1}) and heated spraying systems (K_La = 0.297 h^{-1}). Higher rotational speeds (900 - 1200 rpm) improved ARE and K_La, making HP2R comparable to other methods like conventional stripping and struvite precipitation. Swine wastewater required more fresh air than synthetic wastewater to achieve similar ARE and K_La. At high pre-alkalinization pH, carbonate salts and co-precipitated solids formed, risking clogging, which could be mitigated by high rotational speeds. These findings provide a basis for future studies on continuous HP2R operation and its field application.

Acknowledgements. This research was funded by the 2022 Senior Researcher Program (Grant number: NCVCC30.04/22-23) and by the Vietnam Academy of Science and Technology (VAST) (Grant number: VAST07.03/22-23). Trinh Minh Viet was funded by the Master, PhD Scholarship Programme of Vingroup Innovation Foundation (VINIF), code [VINIF.2023.TS.149].

CRediT authorship contribution statement. Viet M. Trinh: Experimental conduction, Manuscript preparation, Manuscript revision. Phuong Thao Nguyen: Experimental conduction, Formal analysis. Van Tuyen Trinh: Funding acquisition, methodology, manuscript revision. Huu Tung Pham: Experimental conduction. Van Manh Do: Manuscript revision. Thanh Long Ngo: Supervision

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

1. VNA. - Vietnam needs to promote livestock value chain development, 2022. https://link.gov.vn/Q2LczwxV (Accessed 31 Jannuary 2023).
2. Dinh T. X. - An Overview of Agricultural Pollution in Vietnam: The Livestock Sector. World Bank, World Bank eLibrary - York University, (2017)
3. MONRE - The National Environmental Report 2018: Water Quality in River Basins. Ministry of Natural Resources and Environment, (2018)
4. Sakar S., Yetilmezsoy K., Kocak E. - Anaerobic digestion technology in poultry and livestock waste treatment — a literature review. Waste Management & Research, **27** (1) (2009) 3-18 10.1177/0734242X07079060.
5. Dan N. H., Rene E. R., Le Luu T. - Removal of Nutrients From Anaerobically Digested Swine Wastewater Using an Intermittent Cycle Extended Aeration System. Frontiers in Microbiology **11** (2020) 10.3389/fmicb.2020.576438.
6. Loan D. T. T. - Challenges and solutions for storage and treatment of livestock waste, Vietnam Journal of Science, Technology and Engineering, 2022 (https://vjst.vn/vn/tin-tuc/6745/nhung-kho-khan-va-giai-phap-thu-gom-va-xu-ly-chat-thai-ran-chan-nuoi.aspx) (Accessed 1 February 2023)
7. Giang N. T. H., Huong L. T. T., Yabe M., Thang N. T., Hieu V. N., Son C. T. - Recycling Wastewater in Intensive Swine Farms: Selected Case Studies in Vietnam. Journal- Faculty of Agriculture Kyushu University, **66** (1) (2021) 115-121
8. Rajagopal R., Massé D. I., Singh G. - A critical review on inhibition of anaerobic digestion process by excess ammonia. Bioresource technology, **143** (2013) 632-641 10.1016/j.biortech.2013.06.030.
9. Krakat N., Demirel B., Anjum R., Dietz D. - Methods of ammonia removal in anaerobic digestion: a review. Water Science and Technology, **76** (8) (2017) 1925-1938 10.2166/wst.2017.406.
10. Chang H., Lu M., Zhu Y., Zhang Z., Zhou Z., Liang Y., Vidic R. D. - Consideration of Potential Technologies for Ammonia Removal and Recovery from Produced Water. Environmental Science & Technology, **56** (6) (2022) 3305-3308 10.1021/acs.est.1c08517.
11. Tuan Minh N., Van Tuyen T., Thi Phuong Thao N., Huu Tung P., Minh Viet T. - Research on the recycling of waste activated sludge as an adsorbent material for ammonium removal in wastewater. Vietnam Journal of Science and Technology, **60** (3) (2022) 541-553 10.15625/2525-2518/16491.
12. Trinh M. V., Nguyen T. M., Nguyen P. T., Pham H. T., Phung L. P., Dinh K. T., Trinh V. T. - Continuous removal of COD and ammonium from landfill leachate using adsorption columns packed with modified steel slag and blast-furnace slag. Vietnam Journal of Science and Technology, **60** (5B) (2022) 73-87 10.15625/2525-2518/17381.
13. Lorick D., Macura B., Ahlström M., Grimvall A., Harder R. - Effectiveness of struvite precipitation and ammonia stripping for recovery of phosphorus and nitrogen from anaerobic digestate: a systematic review. Environmental Evidence, **9** (2020) 27 10.1186/s13750-020-00211-x.

14. Trinh M. V., Nguyen T. M., Trinh V. T., Do V. M., Ngo T. L., Chen Y.-H., Yuan M.-H. - Evaluation of the operational factors affecting the stripping efficiency of ammonia from aqueous solution using a High-performance Rotating Reactor (HP2R). Vietnam Journal of Science and Technology, **60** (5B) (2022) 265-279 10.15625/2525-2518/17383.
15. Zangeneh A., Sabzalipour S., Takdatsan A., Yengejeh R. J., Khafaie M. A. - Ammonia removal form municipal wastewater by air stripping process: An experimental study. South African Journal of Chemical Engineering, **36** (2021) 134-141 https://doi.org/10.1016/j.sajce.2021.03.001.
16. dos Santos H. A. P., de Castilhos Júnior A. B., Nadaleti W. C., Lourenço V. A. - Ammonia recovery from air stripping process applied to landfill leachate treatment. Environmental Science and Pollution Research, **27** (2020) 45108-45120 10.1007/s11356-020-10397-9.
17. Ferraz F. M., Povinelli J., Vieira E. M. - Ammonia removal from landfill leachate by air stripping and absorption. Environmental technology, **34** (2013) 2317-2326 10.1080/09593330.2013.767283.
18. Bonmatí A., Flotats X. - Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion. Waste Management, **23** (2003) 261-272 https://doi.org/10.1016/S0956-053X(02)00144-7.
19. Guštin S., Marinšek-Logar R. - Effect of pH, temperature and air flow rate on the continuous ammonia stripping of the anaerobic digestion effluent. Process Safety and Environmental Protection, **89** (1) (2011) 61-66 https://doi.org/10.1016/j.psep.2010.11.001.
20. Huang J.-C. and Shang C.- Air Stripping, in Wang L.K., Hung Y.T., and Shamas N.K. (Eds.), Advanced Physicochemical Treatment Processes, Humana Press, New Jersey, 2006, pp. 47-79.
21. Mehairbi M., Mahri S., Dadach Z. E. - Simulation of Stripper Flooding Due to the Increase of Feed Flowrate. World Journal of Engineering and Technology, **08** (3) (2020) 443-455 10.4236/wjet.2020.83033.
22. Cortes Garcia G. E., van der Schaaf J., Kiss A. A. - A review on process intensification in HiGee distillation. Journal of Chemical Technology & Biotechnology, **92** (6) (2017) 1136-1156 https://doi.org/10.1002/jctb.5206.
23. Gudena K., Rangaiah G. P., Lakshminarayanan S. - Optimal Design of a Rotating Packed Bed for VOC Stripping from Contaminated Groundwater. Industrial & Engineering Chemistry Research, **51** (2) (2012) 835-847 10.1021/ie201218w.
24. Im D., Jung H., Lee J. H. - Modeling, simulation and optimization of the rotating packed bed (RPB) absorber and stripper for MEA-based carbon capture. Computers & Chemical Engineering, **143** (2020) 107102 https://doi.org/10.1016/j.compchemeng.2020.107102.
25. Trinh V. M., Yuan M.-H., Chen Y.-H., Wu C.-Y., Kang S.-C., Chiang P.-C., Hsiao T.-C., Huang H.-P., Zhao Y.-L., Lin J.-F., Huang C.-H., Yeh J.-H., Lee D.-M. - Chlorine dioxide gas generation using rotating packed bed for air disinfection in a hospital. Journal of Cleaner Production, **320** (2021) 128885 https://doi.org/10.1016/j.jclepro.2021.128885.
26. Yuan M.-H., Chen Y.-H., Tsai J.-Y., Chang C.-Y. - Ammonia removal from ammonia-rich wastewater by air stripping using a rotating packed bed. Process Safety and Environmental Protection, **102** (2016) 777-785 https://doi.org/10.1016/j.psep.2016.06.021.

27. Yuan M.-H., Chen Y.-H., Tsai J.-Y., Chang C.-Y. - Removal of ammonia from wastewater by air stripping process in laboratory and pilot scales using a rotating packed bed at ambient temperature. Journal of the Taiwan Institute of Chemical Engineers, **60** (2016) 488-495 https://doi.org/10.1016/j.jtice.2015.11.016.
28. Tran L., Le T., Nguyen T., Tran Q., Le X., Pham Q., Lam V., Manh D. - Simultaneous removal efficiency of H2S and CO2 by high-gravity rotating packed bed: Experiments and simulation. Open Chemistry, **19** (1) (2021) 288-298 10.1515/chem-2020-0187.
29. Kinidi L., Tan I. A. W., Abdul Wahab N. B., Tamrin K. F. B., Hipolito C. N., Salleh S. F. - Recent Development in Ammonia Stripping Process for Industrial Wastewater Treatment. International Journal of Chemical Engineering, **2019** (1) (2019) 3181087 10.1155/2018/3181087.
30. MONRE - National Technical Regulation on the effluent of livestock. QCVN 62-MT:2016/BTNMT (2016)
31. MOST - Water - Determination of ammonia content - Ammonia selective electrode method. TCVN 7872:2008 (2008)
32. Petříček R., Moucha T., Rejl F. J., Valenz L., Haidl J., Čmelíková T. - Volumetric mass transfer coefficient, power input and gas hold-up in viscous liquid in mechanically agitated fermenters. Measurements and scale-up. International Journal of Heat and Mass Transfer, **124** (2018) 1117-1135 https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.045.
33. Chen Y.-S., Lin C.-C., Liu H.-S. - Mass Transfer in a Rotating Packed Bed with Various Radii of the Bed. Industrial & Engineering Chemistry Research, **44** (20) (2005) 7868-7875 10.1021/ie048962s.
34. Chen Y.-S., Lin C.-C., Liu H.-S. - Mass Transfer in a Rotating Packed Bed with Viscous Newtonian and Non-Newtonian Fluids. Industrial & Engineering Chemistry Research, **44** (4) (2005) 1043-1051 10.1021/ie0499409.
35. NIST Chemistry WebBook: NIST Standard Reference Database Number *69*; Vol. 2023.
36. Xingjian J., Zihong C., Wei M., Zhanxian G., Xuehu M., Ren W. - Removal of Ammonia from Wastewater by Natural Freezing Method. International Conference on Chemical, Material and Food Engineering (CMFE-2015), (2015) 174-177 10.2991/cmfe-15.2015.41
37. Burns J. R., Jamil J. N., Ramshaw C. - Process intensification: operating characteristics of rotating packed beds — determination of liquid hold-up for a high-voidage structured packing. Chemical Engineering Science, **55** (13) (2000) 2401-2415 https://doi.org/10.1016/S0009-2509(99)00520-5.
38. Hanley B. L., MA, US).- Method of determining flood points of packed columns.United States Patent; (2013).
39. Cao L., Wang J., Zhou T., Li Z., Xiang S., Xu F., Ruan R., Liu Y. - Evaluation of ammonia recovery from swine wastewater via a innovative spraying technology. Bioresource technology, **272** (2019) 235-240 https://doi.org/10.1016/j.biortech.2018.10.021.
40. Huang H., Zhang P., Zhang Z., Liu J., Xiao J., Gao F. - Simultaneous removal of ammonia nitrogen and recovery of phosphate from swine wastewater by struvite electrochemical precipitation and recycling technology. Journal of Cleaner Production, **127** (2016) 302-310 https://doi.org/10.1016/j.jclepro.2016.04.002.