

Review Article

Recent Development in Ammonia Stripping Process for Industrial Wastewater Treatment

Lennevey Kinidi ¹, Ivy Ai Wei Tan ¹, Noraziah Binti Abdul Wahab,¹
Khairul Fikri Bin Tamrin ², Cirilo Nolasco Hipolito,¹ and Shanti Faridah Salleh¹

¹Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

²Department of Mechanical and Manufacturing, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

Correspondence should be addressed to Lennevey Kinidi; lennybb93@outlook.com

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It is noteworthy to highlight that ammonia nitrogen contamination in wastewater has been reported to pose a great threat to the environment. This conventional method of remediating ammonia nitrogen contamination in wastewater applies the packed bed tower technology. Nevertheless, this technology appears to pose several application issues. Over the years, researchers have tested various types of ammonia stripping process to overcome the shortcomings of the conventional ammonia stripping technology. Along this line, the present study highlights the recent development of ammonia stripping process for industrial wastewater treatment. In addition, this study reviews ammonia stripping application for varied types of industrial wastewater and several significant operating parameters. Furthermore, this paper discusses some issues related to the conventional ammonia stripper for industrial treatment application. Finally, this study explicates the future prospects of the ammonia stripping method. This review, hence, contributes by enhancing the ammonia stripping treatment efficiency and its application for industrial wastewater treatment.

1. Introduction

Human activities appear to be the major contributor to water pollution, for instance, agricultural, industrial, and municipal activities. Nitrogen surplus released into the environment has been proven to cause negative impacts on water qualities, human health, and ecosystems [1]. Nonetheless, a wide range of technologies is available to reduce the release of ammonia nitrogen into the environment, such as ammonia stripping [2], breakpoint chlorination [3], ion exchange [4], electro-dialysis [5], and biological nitrification [6]. The ammonia stripping method has several plus points as it is a relatively simple process and cost-effective to remove ammonia in wastewater [7]. Besides, the valuable ammonia stripped from wastewater can be recovered from the stripping process. Due to the stability of this process, the ammonia stripping process has been deemed as an appropriate method in remediating wastewater that contains high concentration of ammonia and toxic compounds [8]. Consequently, ammonia stripping

has emerged as a strong interest research area among researchers and industrial community. As such, numerous lab-scale and pilot-scale studies have been performed, especially for the wide range of industrial wastewater that demands cost-effective remediation.

This paper looks into several emerging issues pertaining to remediating ammonia nitrogen by using the ammonia stripper technique, along with some significant operating parameters. In addition, this paper reviews the recent progress in ammonia stripping method with advanced gas-liquid contactors, as conducted by some researchers. Next, a comparison was made between the advanced liquid contactors and the conventional packed tower. Finally, this paper explores the future prospects of this ammonia stripping process.

2. Ammonia Stripping Process

The ammonia stripping process is based on the principle of mass transfer. It is a process, by which wastewater is contacted

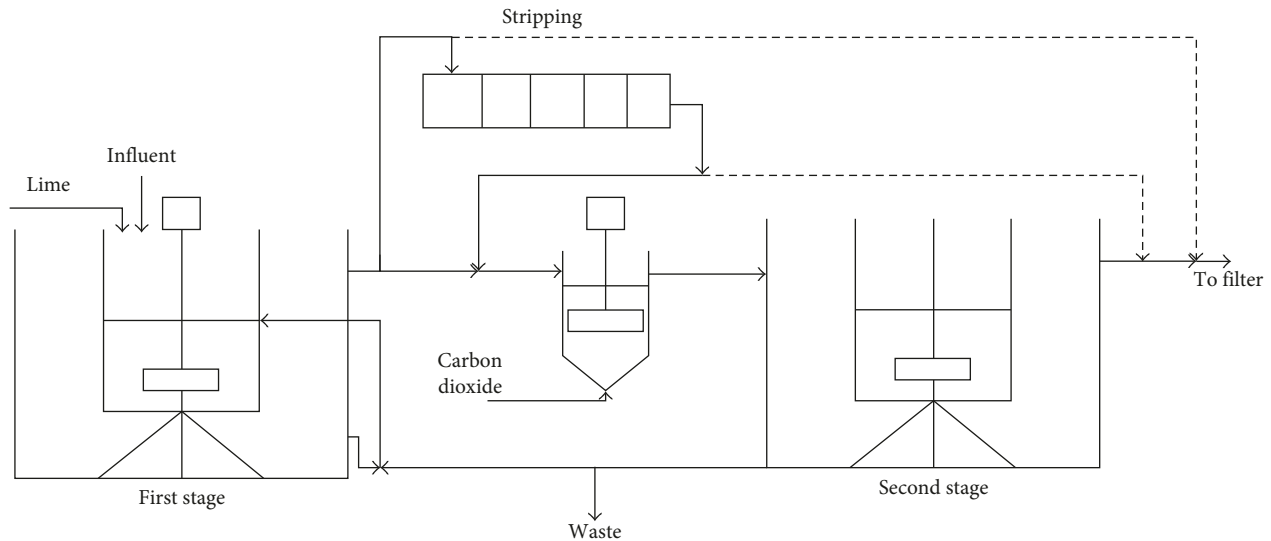


FIGURE 1: Schematic ammonia stripping process for leachate-polluted groundwater [10].

with air to strip the ammonia gas present in the wastewater. The presence of ammonia in wastewater can be found in two forms, namely, ammonium ions and ammonia gas. The relative concentrations of ammonia gas and ammonium ions are subjected to the pH and the temperature of wastewater [9]. The formation of ammonia gas is favored by increasing the pH, which shifts the chemical equilibrium to the right, thus inducing the formation of ammonia gas. Since high pH is required for effective ammonia stripping, lime is used to increase the pH values of wastewater prior to ammonia stripping [9]. In fact, various types of configurations for ammonia stripping process have been applied to remediate the varied types of wastewater containing ammonia nitrogen. For instance, O'Farell et al. conducted a study on nitrogen removal by stripping on a secondary effluent of a municipal wastewater treatment plant [10]. Figure 1 illustrates a schematic diagram of lime precipitation process and ammonia stripping process. Lime is incorporated to hike the pH of the influent prior to stripping, and this is followed by a recarbonation process for neutralization. Aside from raising the wastewater pH, calcium oxide (lime) generates calcium carbonate in the wastewater and serves as a coagulant for hard and particulate matters. Additionally, O'Farell et al. discovered that the ammonia stripping method could remove as much as 90% of ammonia from the secondary effluent [10].

Meanwhile, Raboni et al. investigated the efficiency of the ammonia stripping technique for remediation of groundwater polluted with leachate [11] (Figure 2). In the study, polyelectrolyte, sodium hydroxide, and iron (iii) chloride were added for the coagulation-flocculation and sedimentation processes at pH higher than 11 [11]. The system also comprised of a heater to heat the wastewater at 38°C and ammonia recovery via absorption with sulphuric acid. Lastly, the effluent was neutralized after adding sulphuric acid. As a result, they found that the ammonia stripping system for groundwater polluted with leachate displayed removal efficiency of 95.4% with initial ammonia concentration at 199.0 mg/L.

Next, Saracco and Genon investigated the performance of air-stripping system to treat ammonia nitrogen from industrial effluent (Figure 3) [12]. They suggested this route as feasible only if the industrial effluent was characterized by relatively high temperature and ammonia concentration. The stripping process was followed by absorption and crystallization processes. Saracco and Genon concluded that the ammonia stripping and the recovery system, along with its internal air recycle, had been technically feasible and easy to control [12].

3. Ammonia Stripping Application in Industrial Wastewater Treatment

To date, ammonia stripping pilot-plants have been employed to treat various types of wastewater containing high concentrations of ammonia and toxic compounds, such as that derived from secondary effluent of municipal wastewater treatment plant [10], animal manure [13], and landfill leachate [14]. Most recently, ammonia stripping was applied to anaerobic-digested effluent as this method offers both economic and environmental advantages. The biogas produced in the anaerobic digestion was used for ammonia removal to prevent inhibition of methanogenesis in the anaerobic reactor [15–17]. Meanwhile, Bonmati and Flotats revealed that no pH modification was required for stripping of ammonia from pig slurry [18]. On the other hand, Limoli et al. investigated ammonia removal from raw manure digestate by employing the turbulent mixing stripping process. They found that the ammonia stripping process via turbulent mixing was indeed feasible for raw manure digestate [19].

Table 1 shows that the ammonia stripping technique is indeed highly efficient in treating wastewater that contains ammonia nitrogen with toxic compounds. Besides, ammonia stripping combined with anaerobic digestion seemed to enhance the performance of anaerobic digestion process, apart from being cost-effective for ammonia removal.

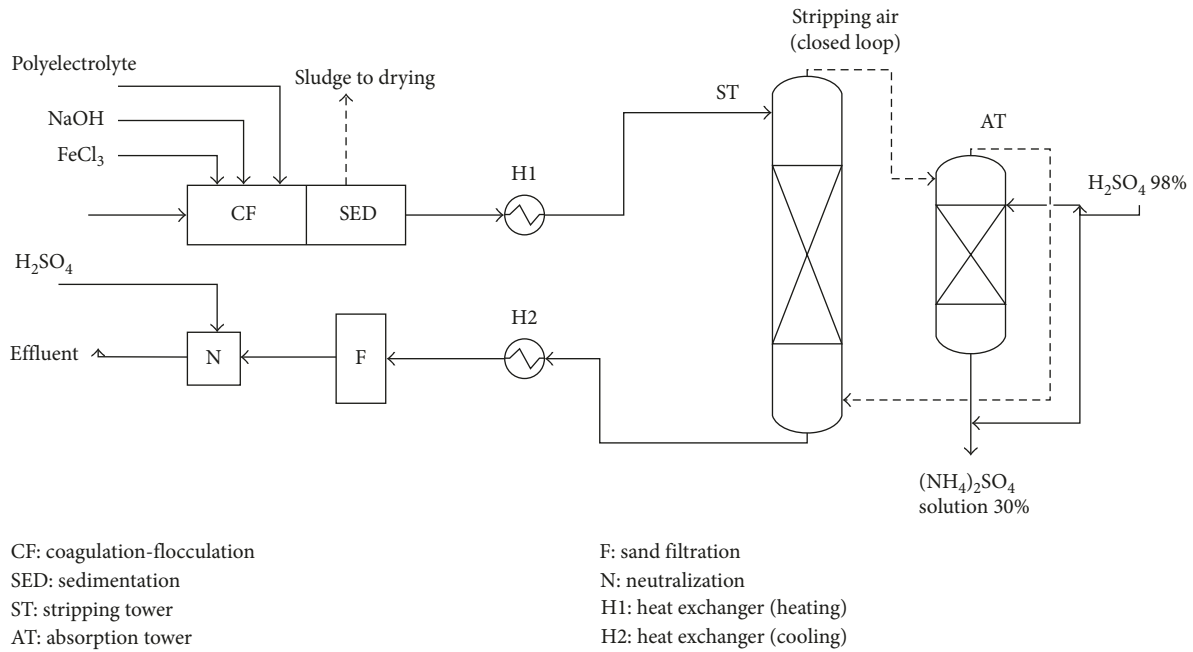


FIGURE 2: Schematic ammonia stripping process for leachate-polluted groundwater [11].

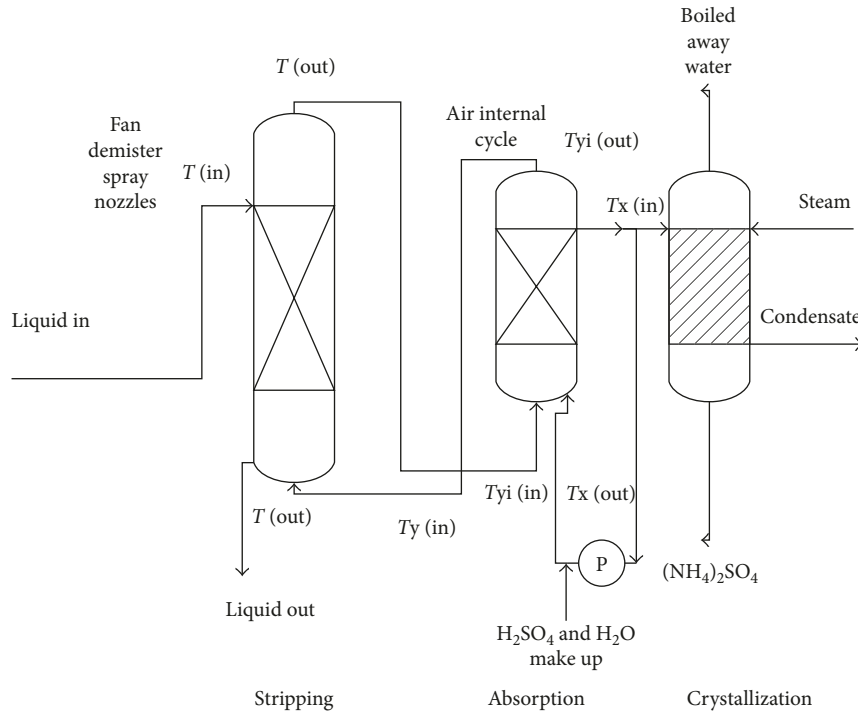


FIGURE 3: Proposed plant for ammonia stripping for industrial effluent application [12].

Nonetheless, Serna-Maza et al. revealed that in-situ ammonia stripping in mesophilic condition was unlikely to have any commercial application for wastes with intermediate total ammonia nitrogen concentrations as only high total ammonia nitrogen concentration stripping had managed to reduce the total ammonia nitrogen concentration below the higher inhibition threshold of approximately $8 \text{ g}\cdot\text{N}\cdot\text{L}^{-1}$ [29]. Thus, stripping coupled with dilution

may offer the best means of controlling total ammoniacal nitrogen concentrations. Next, Collivignarelli et al. found that ammonia stripping without dosage of basicant had been feasible when the initial alkalinity of the leachate was equal to or greater than the acidity of ammonium ions for removal [30]. Notably, this can potentially minimize chemical usage and slash operational cost in removing ammonia nitrogen from leachate. Ammonia stripping also

TABLE 1: Several studies that had looked into the ammonia stripping process with varied types of industrial wastewater.

Wastewater	Ammonia stripping reactor	Influent ammonia (mg/L)	Ammonia removal percentage (%)	Operating condition	Reference
Biologically treated blue crab processing wastewater	Packed bed	2300	72	Liquid loading rate: 25 L/m ² /min Temperature: 14°C pH: 12.0	[20]
Petroleum refinery wastewater	Packed bed	100	85	Airflow rate: 8495.1 L of air/gal of wastewater Temperature: 25°C pH: 10.5	[21]
Landfill leachate	Packed bed	1213	88	Airflow rate: 4500 L·h ⁻¹ Temperature: 25°C pH: 11	[22]
Piggery wastewater	Packed bed	4950	80	Airflow rate: 10 L/min Temperature: 37°C pH: 11	[23]
Fertilizer effluent	Packed bed	2000	99	Airflow rate: 420 m ³ ·m ⁻² ·h ⁻¹ Temperature: 26°C pH: 11	[24]
Raw manure digestate	Mixer	5000	88.7	Temperature: 23°C pH: 10	[19]
Secondary effluent	Packed bed	12	86.2	Airflow rate: 100 L/min/sq-m Temperature: 20.6°C pH: 11.7	[10]
Acetylene purification wastewater	Packed bed	125	91%	Airflow rate: 0.5 m ³ /h Temperature: 60°C pH: 12	[25]
Ammonia-rich soda ash wastewater	Microwave-assisted air stripping	1350	96.3%	pH: 11; time: 5 mins microwave radiation power: 750 W	[26]
Sludge liquor from municipal wastewater treatment plants	Ion exchanger loop stripping	2300	84.6%	pH: 10.5	[27]
Swine wastewater	Microwave-assisted air stripping	2740	88.2	pH: 11 microwave radiation: 700 W	[28]

appears to be effective and suitable in agriculture due to its simple process and cost-effectiveness in removing ammonia efficiently.

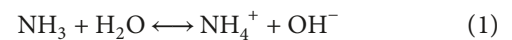
4. Process Condition

Numerous studies have highlighted the impacts of varying operational parameters upon the performance of ammonia stripping process. Some important parameters that have been reported to influence the performance of ammonia stripping are temperature, pH, and air to water ratio.

4.1. Temperature. Temperature has been proven to have a significant impact on the performance of ammonia stripper. This is because the solubility of ammonia in water is governed by Henry's law. In Henry's law, the constant of gas relies on solute, solvent, and temperature [31]. For example, Campos et al. discovered that the removal of ammonia from landfill leachate at 60°C was relatively significant over a period of 7 hours than at 25°C [32]. Generally, higher efficiency ammonia removal can be obtained at higher temperature. Saracco and Genon also found that the capital

cost of ammonia stripper at a stripping temperature of 80°C was less by half than that at 40°C. Nevertheless, from the economic stance, increment in temperature may lead to a hike in the cost of preheating [12].

4.2. pH. Ammonia nitrogen in water exists in equilibrium between the molecular (NH₃) and ionic form (NH₄⁺) according to the following reaction:



The distribution between molecular ammonia and ammonium ions in water can be defined by (2) [16] and (3) [18]:

$$[\text{NH}_3] = \frac{[\text{NH}_3 + \text{NH}_4^+]}{1 + [\text{H}^+]/K_a} \quad (2)$$

$$pK_a = 4 \times 10^{-8}T^3 + 9 \times 10^{-5}T^2 + 0.0356T + 10.072, \quad (3)$$

where [NH₃] is the molecular ammonia concentration, [NH₃ + NH₄⁺] is the total ammonia concentration, [H⁺] is the hydrogen ion concentration, and K_a is the acid ionization constant. Besides that, pK_a can be expressed in terms

of temperature as shown in (3). Higher pH favors the formation of ammonia gas whereas lower pH favors the formation of ammonium ions. Hence, raising the pH level of the wastewater prior ammonia stripping is crucial to favor the formation of molecular ammonia nitrogen for stripping. However, according to Hidalgo et al., excessive rise of pH poses extra cost of lime that is nonfeasible in terms of cost. Hence, an optimum pH is required to strike a balance between process efficiency and economic cost. They found that when the pH exceeded 10.5, the removal efficiency was insignificant because pH no longer affected the ionization balance between molecular ammonia and ionic ammonium but the cost incurred rose significantly due to the additional lime consumption required to increase the pH levels [33]. Meanwhile, Markou et al. revealed insignificant effect for the types of alkali (potassium hydroxide, sodium hydroxide, and calcium hydroxide) used on the ammonia removal efficiency [34]. However, calcium alkali was preferable due to reduction of solids, heavy metal concentrations, and color of wastewater [35].

4.3. Air to Water Ratio. Air to water ratio is an important parameter that has an impact on the removal rates of ammonia in water. Mass transfer of ammonia into the air is affected by the variance between ammonia concentration level in liquid form and air phase [18]. Lei et al. discovered that the ammonia stripping efficiency of anaerobic effluent was influenced by air/water ratios. The study found that higher ammonia removal rate was achieved after 12 h at an airflow rate of 10 L/min, in comparison to airflow rates at 3 L/min and 5 L/min [16]. Nevertheless, from the engineering stance, Lei et al. concluded that 5 L/min for 1 L of anaerobic effluent should be feasible due to the expensive method of using an airflow rate of 10 L/min for 1 L of wastewater with only 5% increment in removal efficiencies, as compared to airflow rates from 5 L/min until 10 L/min [16]. Next, Campos et al. revealed that the influence of air to water ratio on ammonia stripping performance at higher temperature was less significant as it resulted in ammonia removal greater than 91% at 60°C with an airflow rate between 73 L/h and 120 L/h [32].

5. Issues Related to Ammonia Stripper Wastewater in Industrial Treatment Application

The ammonia stripping process has been successfully employed for many types of high-strength ammonia wastewater (Table 1). The method refers to one that is controlled and unaltered by toxic compounds. Nevertheless, the ammonia stripping process has several drawbacks. Among the issues involving the implementation of ammonia stripper to remove ammonia nitrogen in wastewater are fouling problems, sludge production, and release of ammonia gas.

5.1. Fouling Problems. The fouling problems in an ammonia stripper tower are caused by the formation of calcium carbonate scale on the surface of the packing materials. Scale

builds up on the packing materials, thus leading to lower stripping performance [32]. Viotti and Gavasci found that the progressive scaling of the packing reduced stripper efficiency from 98% to 80% after 6 months of operation. The formation of calcium carbonate scale on the packing material is due to the absorption of carbon dioxide from the air stream used for stripping. Moreover, the nature of calcium carbonate varies from soft to hard. Viotti and Gavasci, thus, suggested chemical cleaning to attain higher removal of ammonia from wastewater [36]. The high operation and maintenance cost for air stripping can be attributed to the formation of calcium carbonate scale [37].

5.2. Sludge Production. The stripped effluent of ammonia stripping often fails in meeting the discharge standards. High sludge production and high alkalinity effluent associated with ammonia stripping generate additional treatment cost to this process. However, the calcium carbonate from the ammonia stripper sludge can be recovered. Maree and Zvinowanda, for example, used the flotation technique to recover calcium carbonate from wastewater treatment sludge [38]. As a result, they discovered that flotation technique can potentially recover commercial grade limestone from wastewater sludge [38]. Meanwhile, He et al. assessed the feasibility and performance enhancement for treatment of alkaline-stripped effluent in aerated constructed wetlands [39]. The constructed wetland was relatively simple and was empowered with eco-friendly technology so that it can withstand extreme pH wastewater. He et al. also found that the remediation of alkaline effluent was feasible due to the high buffering capacity of the wetlands [39].

5.3. Ammonia Gas. The ammonia stripping process results in ammonia release into the environment, thus causing additional environmental issues. Ammonia recovery by absorption is generally employed to prevent ammonia gas from being directly released into the environment. Ferraz et al. used sulphuric acid to recover the stripped ammonia from landfill leachate and revealed that 87% of the stripped ammonia was recovered [22]. Next, Zhu et al. discovered that under optimal condition of pH 12, airflow rate of 0.50 m³/h, temperature of 60°C, and stripping time of 120 min; 0.2 mol/L of sulphuric acid can absorb approximately 93% of the ammonia stripped per volume of the acetylene purification wastewater [25]. Meanwhile, Laurenzi et al. concluded that ammonia stripping coupled with absorption proved to be a feasible option for valorization of nitrogen found in pig slurry. The by-product of this process was ammonium sulphate, which is a marketable product in the agriculture arena as fertilizers [15].

6. Advances in Ammonia Stripping Process

Research on ammonia stripping enhancement has continued unabated. Recent development of ammonia removal by ammonia stripping fall into the following: ammonia stripping reactor modifications, membrane contactor, membrane

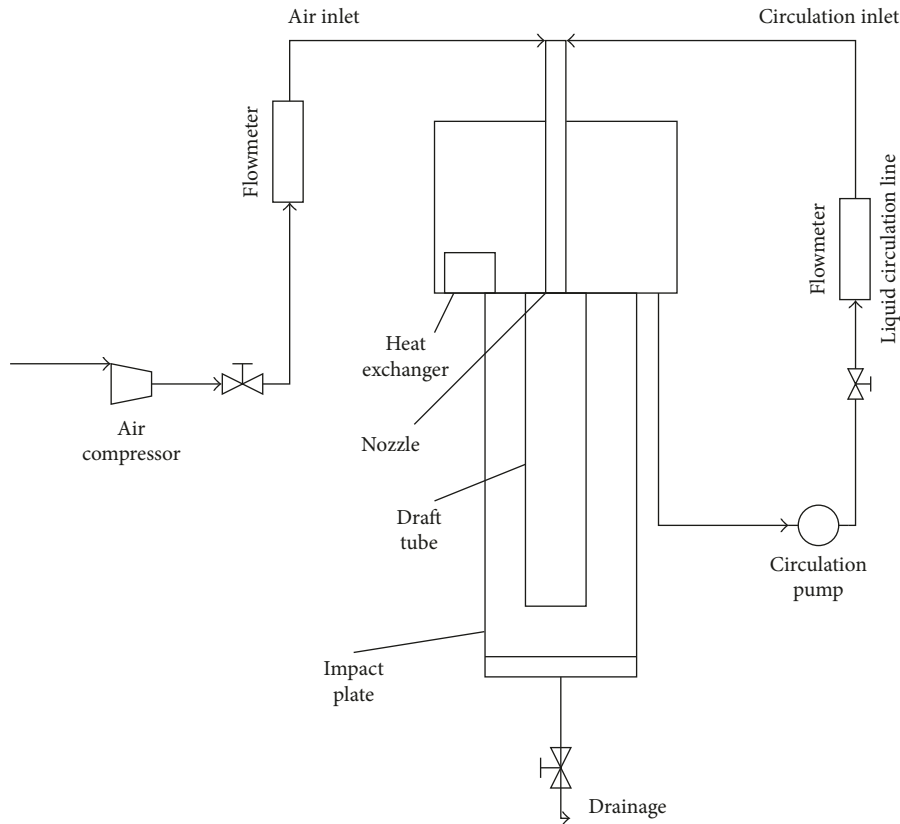


FIGURE 4: Schematic diagram of jet loop reactor [42].

distillation, ion exchange-stripping loop, and microwave-assisted ammonia stripping.

6.1. Ammonia Stripping Reactor Modifications. The construction of a particular ammonia stripping reactor is crucial as it has a strong impact on the whole treatment efficiency and the capital cost. The conventional ammonia stripper reactor employs the packed column technology, in which the packing materials are used to enhance mass transfer between the two phases. The countercurrent-packed tower draws air through its openings at the bottom as the wastewater is pumped to the top of the packed tower. Nonetheless, this process generates carbonate scales on the surface of the packing materials, which can affect ammonia removal efficiencies over time. Apart from that, the average depth of the packed bed tower can range from 6.1 until 7.6 meters, hence consuming a considerably large amount of space. Therefore, some researchers have suggested the use of innovative ammonia stripper reactors as a solution for efficient removal of ammonia. Among the innovative ammonia stripping reactors proposed were rotating packed bed [40], water-sparged aerocyclone reactor [41], and semibatch jet loop reactor [42].

6.1.1. Semibatch Jet Loop Reactor. Removal of ammonia via air stripping in a semibatch jet loop reactor was initiated by Degermenci et al., in which ammonia is removed by a jet loop reactor so as to reduce the construction and operational costs

of the conventional ammonia stripping process. It also has a higher mass transfer coefficient and easier adaption from the pilot scale to the industrial-scale [42]. The jet loop reactor was conventionally applied for chemical or biochemical catalyzed reactions [43]. The jet loop reactor offers exceptional mixing performance at relatively low energy consumption for application that involves mass transfer [44].

An overall overview of the jet loop reactor is illustrated in Figure 4. In general, the jet loop reactors were constructed in many designs in terms of apparatus, nozzle dimensions, draft tube, and entry position of the jet stream [45]. The principle of the jet loop reactor is the utilization of the kinetic energy of high-velocity liquid jet to entrain the gas phase, besides producing fine dispersion between the gas and the liquid phases [46].

Degermenci et al. have developed (4) to model the rate of ammonia removal via air-stripping technique in a jet loop reactor [42].

$$-\ln \frac{C_{L,t}}{C_{L,0}} = \frac{K_H Q_G}{V_L} \left[1 - e^{-((K_L a S L e)/(Q_G K_H))} \right] t. \quad (4)$$

As a result, the temperature and the gas flow rate exhibited significant impacts on the ammonia removal rate by using the jet loop reactor. Besides, the jet loop appeared to be more effective than the conventional ammonia stripper packed tower. The jet loop reactors can also be used for the conversion processes in treating biochemical wastewater. Farizoglu et al. studied the treatment of cheese whey in a jet loop membrane reactor and achieved 84–94% of chemical

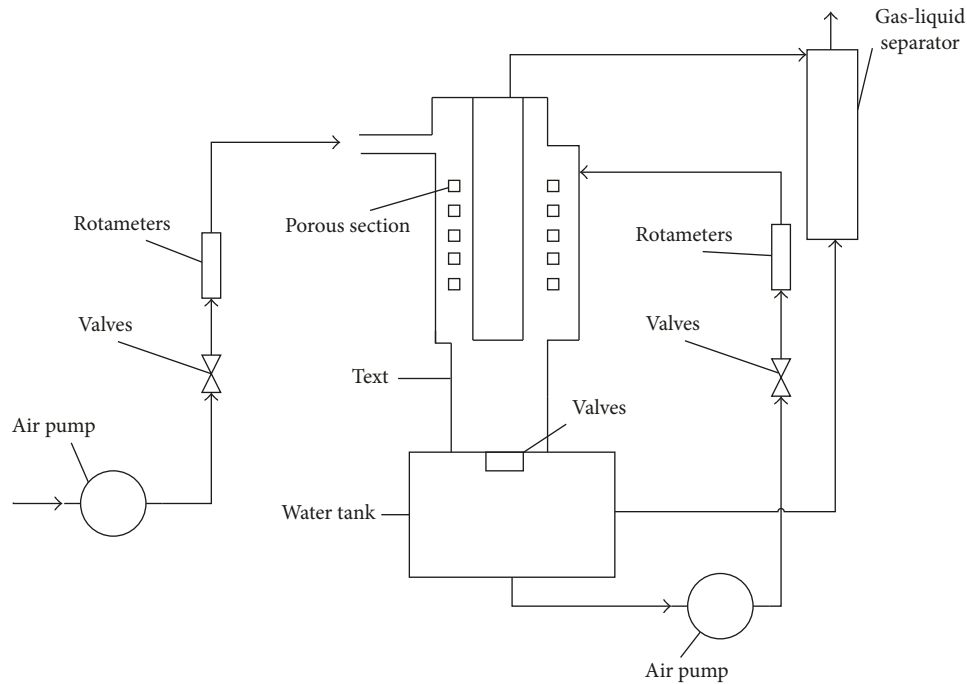


FIGURE 5: Water-sparged aerocyclone reactor configurations.

oxygen demand removal, which possessed the capability to operate at high biomass concentrations [47]. Next, Eusebio et al. investigated the treatment of winery wastewater by using jet loop reactor and found that 80% of COD removal efficiencies had been achieved within 24 hours [48].

6.1.2. Water-Sparged Aerocyclone Reactor. Removal of ammonia via water-sparged aerocyclone reactor was first designed by Quan et al. The basic motivation for the innovation was to increase the mass transfer rate and its applicability to treat wastewater with suspended solids [41]. The water-sparged aerocyclone gas-liquid contactor can be used to address two major drawbacks of the conventional packed tower, which are the process performance and the fouling problems in long operations.

The water-sparged aerocyclone reactor is illustrated schematically in Figure 5. The water-sparged reactor is comprised of two concentric right-vertical tubes and a cyclone header on the upper section. Wastewater is pumped into the porous section of the inner tube and sprayed into the centerline of the water-sparged aerocyclone reactor. After that, air is drawn into the aerocyclone at the top header of the inner tube.

Quan et al. adopted (5) developed by Matter-Muller et al. to model the ammonia removal rate via air-stripping technique using the water-sparged aerocyclone [49].

$$-\ln \frac{C_{A,t}}{C_{A,0}} = \frac{H_A Q_G}{V_L} \left[1 - e^{-((K_L a V_L) / (Q_G H_A))} \right] t. \quad (5)$$

It was found that the water-sparged aerocyclone removed ammoniacal nitrogen, total phosphorus, and COD from wastewater at 91.0%, 99.2%, and 52.0%, respectively. Due to the promising ammonia removal efficiency by the

water-sparged aerocyclone reactor, the structure of the water-sparged aerocyclone reactor was improved by Quan et al. to maximize the mass transfer efficiency of the reactor [50]. Quan et al. also investigated the arrangement and the diameter of the jet holes in water-sparged aerocyclone reactor, thus concluding that the spray holes should be arranged in a square mode with $1.28 l_c$ of optimum distance between two adjacent spray holes [50].

6.1.3. Rotating Packed Bed Reactors. Ammonia removal via air-stripping technique in the rotating packed bed reactor was conducted by Yuan et al. to enhance the high volumetric gas-liquid mass transfer coefficients, as well as to reduce the fouling problem, the equipment size, and the cost incurred, as an attempt to overcome the shortcomings detected in the conventional ammonia stripping technique. The rotating packed bed reactor appeared to be highly efficient in process intensification as it maximized the gas-liquid mass transfer efficiency via strong centrifugal acceleration [51].

In fact, this particular method have been employed in a number of industrial applications, namely, absorption [52], synthesis of biodiesel [53], hydrogen sulfide removal [54], and synthesis of nanoparticles [55].

The rotating packed bed is illustrated schematically in Figure 6. The rotating packed bed consists of a rotating packed bed, gas and influent controls, effluent analyzer, and effluent gas neutralizer [40].

Yuan et al. used (6) to model the ammonia removal rate via air stripping using the rotating packed bed reactor [40]:

$$K_L a = \frac{Q_L}{V_B} \frac{\ln \left[(1 - (1/S)) (C_{L,in} / C_{L,out}) + (1/S) \right]}{1 - (1/S)}. \quad (6)$$

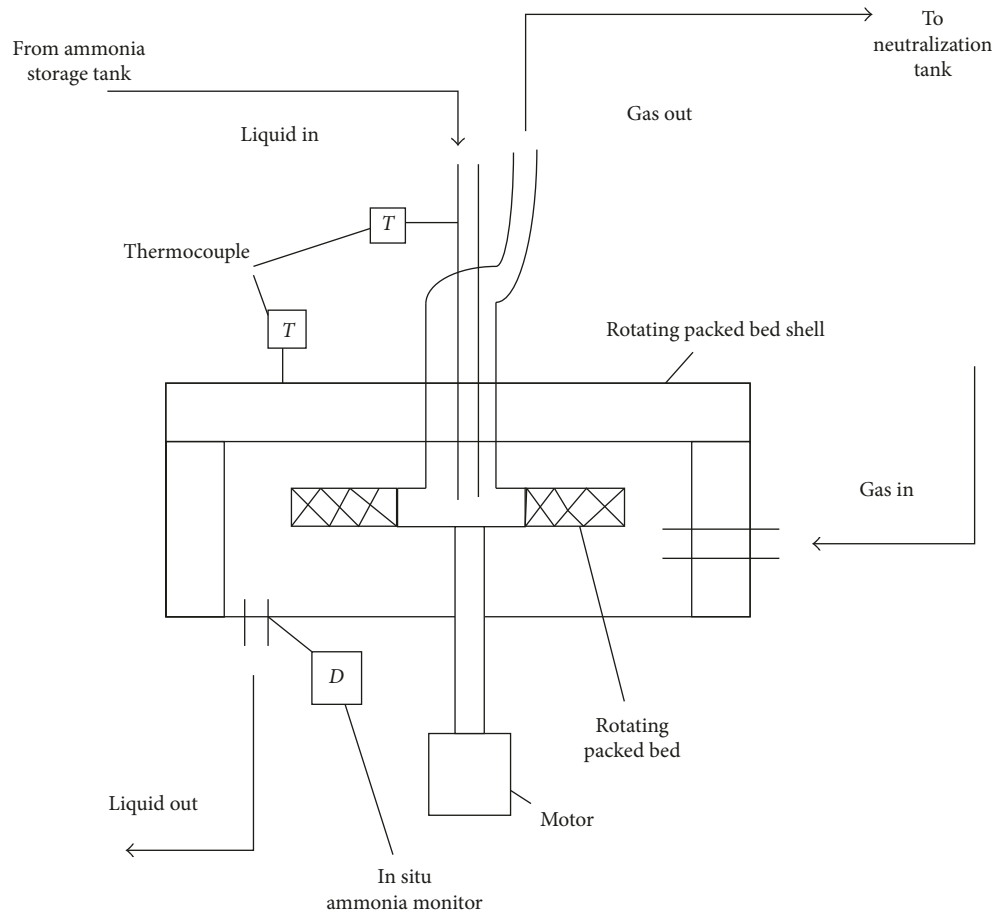


FIGURE 6: Rotating packed bed reactor configuration for ammonia stripping.

It was found that the rotating packed bed displayed higher mass transfer efficiency (12.3–18.41/h), when compared to other conventional and advanced gas-liquid contactors. Nonetheless, information concerning economic feasibility of the operating conditions seemed scarce for packed bed reactors in industrial wastewater treatment [40].

6.2. Membrane Contactors. Ammonia stripping by using membrane contactor is another alternative that has lower tendency to fouling and requires no post effluent treatment [56]. Relatively, ammonia stripping by membrane contactor has a higher rate of mass transfer than the conventional ammonia stripping due to its large contact surface area between the wastewater and stripping solution [57]. Semmens et al. have derived (7) to model the ammonia removal rate by ammonia stripping by using membrane contactor [56]:

$$\ln \frac{C_o}{C} = \frac{Q_t}{V} (1 - e^{-kaL/v}). \quad (7)$$

Ahn et al. have founded that the highest mass transfer coefficient by using PTFE membrane was at 11×10^{-3} m/h at the operating condition of 1000 mg/L of ammonia initial concentration with no suspended solids and temperature difference [57]. Hasanoglu et al. investigated the ammonia removal by using flat sheet and hollow fiber membrane

contactors and founded that the circulation configuration solution has a strong impact on the efficiency of the process [58]. Tan et al. studied the ammonia removal by using polyvinylidene fluoride (PVDF) hollow membranes and founded that mass transfer rate is higher at higher feed velocity, but only up to 0.59 m/s [59]. The ammonia stripping by using membrane contactor is illustrated schematically in Figure 7.

6.3. Membrane Distillation. In recent years, there has been an increasing research on ammonia removal using membrane distillation. Membrane distillation is driven by the temperature difference across the permeable membrane. It offers prospective recycling and reuse of industrial wastewater and higher process efficiency. Membrane distillation can be grouped into four basic configurations, namely, direct contact membrane distillation [60], vacuum membrane distillation [61], air gap membrane distillation [62], and sweep gas membrane distillation [63]. Liu et al. reported that direct contact membrane distillation process ammonia removal rate was more than 85% at ammonia concentration higher than 400 mg/L, but the removal rate decreased as the ammonia concentration was above 1200 mg/L [60]. El-Bourawi et al. addressed that the most important operating parameters that affect the ammonia removal efficiency of

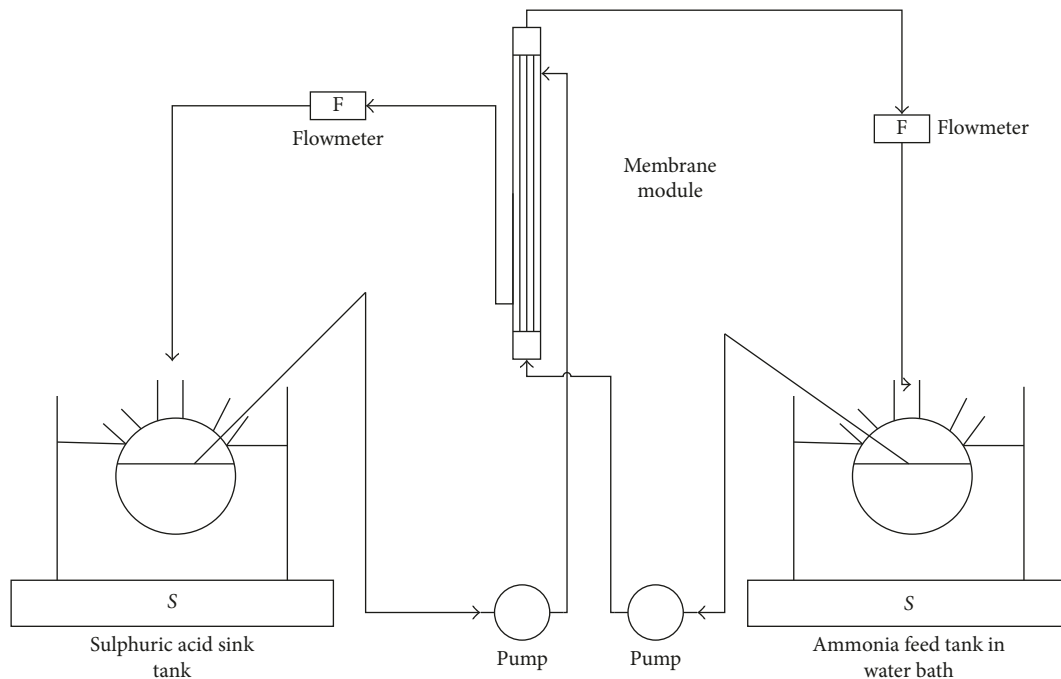


FIGURE 7: Membrane contactor configuration for ammonia stripping [59].

the vacuum membrane distillation are feed temperature, feed flow velocity, and downstream pressure. They reported that ammonia removal efficiencies higher than 90% were achieved by using vacuum distillation [61]. Eykens et al. conducted a lab scale and pilot scale on ammonia stripping by direct contact and air gap membrane distillation. It was founded that air gap membrane distillation has better performance and lower energy requirement than direct contact membrane distillation for larger scale applications [62]. Xie et al. investigated the ammonia removal by sweep gas membrane distillation. The efficiency of the process was affected by the feed temperature, feed flow rate, and gas flow rate. It was founded that sweep gas membrane distillation showed promising result with regards to high-efficiency industrial process water recycling [63]. The removal efficiency of the sweep gas membrane distillation was reported to be up to 97%. Liu et al. reported that the asymmetric PVDF membrane possesses excellent antifouling and sustainable flux in relative with the commercial PTFE (polytetrafluoroethylene) membrane [64]. It was founded that the PVDF membrane has less than 8% flux decline in 15 hours continuous operation [64].

6.4. Ion Exchange Loop Stripping. Due to the problems associated with operating and maintenance costs of air stripping [65] and the economic viability of the resins used for ion exchange [66], ion exchange and air stripping are combined and called ion exchange loop-stripping. The ion exchange loop stripping offers relatively lower operating and investment cost due to the reduced energy demands and equipment size reductions [67]. The ion exchange loop stripping is illustrated schematically in Figure 8. Ion exchange

loop stripping is made up of the zeolite bed, stripping column, and a scrubber.

Ellersdorfer suggested that sodium hydroxide solution may be an alternative to sodium chloride to reduce chemical consumption [27]. Ellersdorfer has investigated the technical feasibility of ammonium recovery by using ion exchange loop stripping for sludge liquor from municipal wastewater treatment plants and founded that it can be a feasible option for recovering ammonium from sludge liquor wastewater treatment plants at above 900 mg/L [27].

6.5. Microwave-Assisted Air Stripping. Reports on microwave radiation that could be used to reduce ammonia nitrogen in wastewater have opened the door for research in the field of ammonia stripping by microwave radiation. Li Lin et al. implemented a pilot-scale study of ammonia removal by using microwave radiation and founded that 80% ammonia removal from coke-plant wastewater can be achieved [26]. Ata et al. carried out studies on optimization of ammonia removal microwave-assisted air stripping and founded that the optimum conditions were at 1800 mg/L of initial concentrations, $7.5 \text{ L}\cdot\text{min}^{-1}$ of airflow rate, 60°C of temperature, 500 rpm of stirring speed, and 200 W microwave output with 60 minutes of radiation. The removal efficiency of microwave-assisted ammonia stripping was able to achieve 94.2% under optimized conditions [68]. La et al. evaluated the efficiencies of microwave-assisted ammonia removal from swine wastewater. The highest removal efficiency was obtained at 83.1%. Ammonia removal by microwave radiation offers high ammonia removal rate and lower reaction time [28]. However, more research is needed for optimizing the power consumption of this wastewater treatment system.

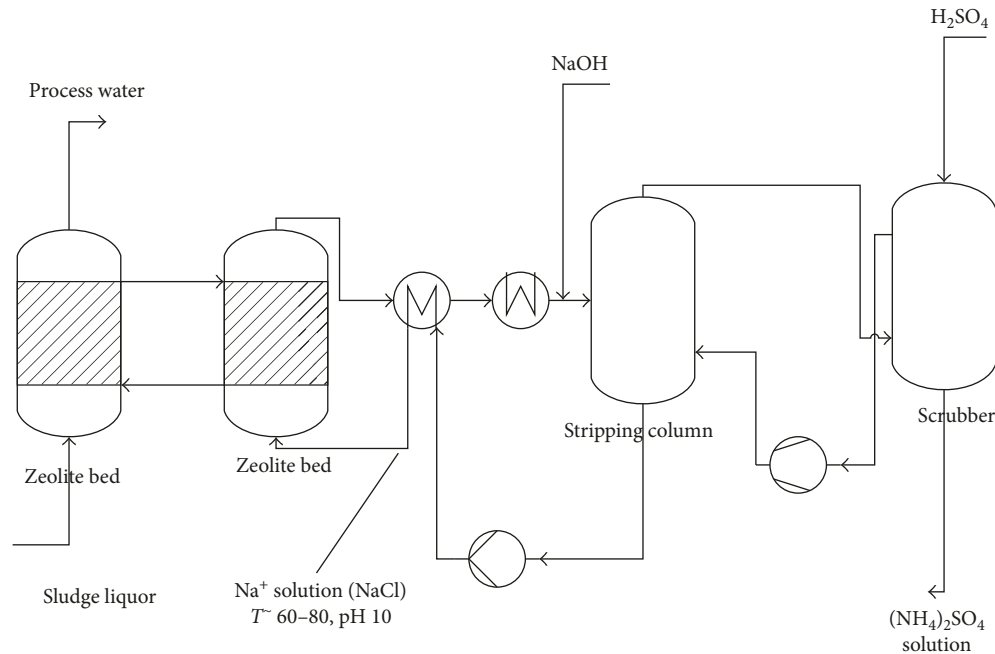


FIGURE 8: Ion exchange loop stripping configurations [27].

7. Comparisons between Different Ammonia Stripping Processes

A comparison of various parameters related to the different ammonia stripping processes based on literature was tabulated in Table 2.

Table 2 shows that among the processes evaluated, the packed tower displayed a higher tendency towards fouling, which decreased its efficiency and increased the operational cost of the whole process. Besides, the packed tower also required higher air consumption, when compared to the other ammonia stripper processes. Besides that, the packed tower also requires higher air consumption in relation with other ammonia stripper processes. However, the newer ammonia stripping processes such as, the semibatch jet loop reactor, water-sparged aerocyclone reactor, and rotating packed bed reactor, have lower tendency towards fouling problems. Since the rotating packed bed reactor operates in continuous flow, Yuan et al. suggested that larger rotating packed bed reactor has to be used to ensure higher process efficiency [40]. The water-sparged aerocyclone also offered simultaneous removal of other contaminants, such as total phosphorus and COD. In addition, the conventional packed tower displayed lower tolerance to total suspended solids. Hence, this technique is limited to applications with lower suspended solids present in wastewater. In this case, the ammonia stripping processes via semibatch jet loop reactor, water-sparged aerocyclone reactor, and rotating packed bed reactor are deemed suitable for wastewater that contains higher total suspended solids. It can also be seen that the implementation membrane technologies in ammonia stripping process have been receiving considerable attention in recent years. Separation technologies using membrane incorporated into the ammonia stripping has higher process

efficiency and offers prospective wastewater reclamation and reuse [72]. However, the membrane technologies are subjected to membrane fouling which results in a substantial increase in hydraulic resistance [73]. Hence, future research should emphasize on the membrane fouling control and the performance on a larger scale. The microwave-assisted ammonia stripping also showed higher process efficiency at 94.2%. Nonetheless, higher power consumption and running costs posed a serious challenge for the microwave-assisted ammonia stripping process [69].

8. Summary of Review and Future Research Perspectives

This review paper has revealed the inherent benefits of the ammonia stripping process, in comparison to the conventional packed tower. Nevertheless, pilot-scale investigation and economic evaluations are required before applying full scale of the ammonia stripping process. Moreover, future researches can specifically focus on the following three aspects.

First, the structure optimization for the each of the ammonia stripping process reactors deserves further research. Since most of the new advanced ammonia stripping reactors were first designed for various types of applications, it is important that these reactors are tailor-made for ammonia stripping processes. One of the most important aspects of ammonia stripping reactor's development refers to the higher air-stripping efficiency at a lower operational cost. Hence, structure optimization can illustrate a detailed design guide for optimized gas-liquid contactors.

Second, more studies are needed to evaluate the capital and operational costs for advanced liquid-gas contactors in ammonia stripping. Since studies regarding these important

TABLE 2: Comparison of the different ammonia stripping processes.

Ammonia stripping processes	Wastewater volume	Process efficiency (%)	Removal of other contaminant	Suspended solids tolerance	Fouling problem	Stripping time (h)	Airflow rate	Mass transfer coefficient	References
Packed tower	1000	75	Not available	Low	High	3.5	25 (air to water ratio)	0.42/h	[69]
Semibatch jet loop reactor	9 L	97	Not available	High	Low	5.8	5.6 (air to water ratio)	0.63/h	[42]
Water-sparged aerocyclone	10 L	98	Total P and COD	High	Low	3.5	11.4 (air to water ratio)	1.2/h	[41]
Rotating packed bed reactor	0.025–0.01 L/min	64	Not available	High	Low	0.0037	1800 L/min (continuous flow)	12.3/h	[40]
Membrane contactor	0.94 L	99.83	Not available	Low	High	10	Not available	0.011 m/h	[57]
Membrane distillation	1 L	98.5	Not available	Low	High	4h	Not available	0.079	[70]
Ion exchange loopstripping	2 L	84.6	Not available	low	High	2.5	Not available	Not available	[27]
Microwave radiation	0.75 L	94.2	Not Available	High	Not available	0.0167	10 (air to water ratio)	3.354	[71]

aspects are in scarcity, and such information is vital to engineers and decision-makers in-charge of devising new technologies, more evaluations are required to look into the full cost analysis of the advanced gas-liquid contactors so as to determine its economic feasibility for specific wastewater treatment scenario. Additionally, a detailed pilot study on the advanced gas-liquid contactors is also crucial to identify potential hiccups and allay investor concerns.

Third, two of the advanced gas-liquid contactors (rotating packed bed and water-sparged aerocyclone) utilize vortex to induce gas-liquid mass transfer. Hence, there is a possibility of harvesting energy from these water vortexes. As such, it has been proposed that the advanced gas-liquid contactors have to be integrated with water vortex generator. This may be a possible strategy to promote energy self-sufficient ammonia stripping process. Nishi and Inagaki investigated the vortex-type water turbine to generate electricity and discovered its ability in generating electricity by using a low head and a low flow rate using a simple structure [74]. This ammonia stripping reactor liquid, coupled with water vortex generator, seems to be a promising technology for energy self-sufficient wastewater treatment and demands further research.

9. Conclusion

Ammonia stripping process is suitable for treating wastewater that contains high concentration of ammonia and toxic compounds with the merits of simpler operation, high efficiency, and excellent treatment stability, thus displaying an exceptional application potential for industrial wastewater treatment. The success of an ammonia stripping process is greatly dependent on temperature, pH, and air to water ratio. As such, the selection of optimized operating parameter is vital for the ammonia stripper to achieve higher efficiency. The different types of ammonia stripping reactors for ammonia stripping are presented in this review article. Its outstanding mass transfer performance and higher total suspended solids tolerance discriminate the conventional packed tower for ammonia stripping method. The following directions are proposed for further research. First, the structure optimization should be done for each of the ammonia stripping processes for higher air-stripping efficiency at a lower operational cost. Secondly, full cost analysis of the advanced ammonia stripper processes is needed to evaluate its economic feasibility for specific wastewater treatment scenario. Lastly, the integration of advanced gas-liquid contactors with vortex power generator for an energy self-sufficient wastewater treatment is proposed.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

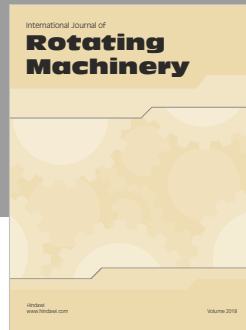
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