Effect of dilution and operating parameters on ammonia removal from scheduled waste landfill leachate in a lab-scale ammonia stripping reactor

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Abstract. A lab-scale ammonia stripping reactor was used to treat raw and diluted (1:1) scheduled waste landfill (SWL) leachate containing ammonia-nitrogen (NH3-N). Operating parameters such as air-liquid ratio, hydrated lime [Ca(OH)2] dosage, types of packing materials and packing heights were investigated with central composite design (CCD) of response surface methodology (RSM) was used to optimize the parameters affecting NH3-N removal from the leachate. The percentage removal on turbidity, colour and phosphate were also evaluated in this study. It was observed that the optimal conditions obtained from desirable response (NH3-N removal) for raw leachate were predicted at air–liquid ratio of 70, Ca(OH)2 dosage of 5 gL−1, packing height of 60 cm and types of packing material was number 3 (non-woven polyester) while for diluted leachate these were 70, 6 gL−1, 60 cm and Type 3 (non-woven polyester), respectively. Quadratic RSM predicted the maximum NH3-N removal to be 78% for raw leachate and 81% for diluted leachate at these optimal conditions concurred with the experiment which successfully removed 76% and 80% of NH3-N, respectively. However, higher removal efficiencies of turbidity (97%), colour (88%) and phosphate (93%) was observed in the treatment with diluted leachate compared to raw leachate merely up to 55%, 34% and 49%, respectively. The finding showed that the difference in the removal of NH3-N in diluted and raw SWL leachate was insignificant. However, turbidity, colour and phosphate showed a significant reduction in the diluted leachate during the treatment. The study suggests that the dilution of SWL leachate does not present a significant effect on the removal of ammonia in the stripping reactor.

1. Introduction
Landfilling is a favorable method for waste disposal due to its low cost, ease of operation and implementation [1]. However, the method generates toxic and highly polluted leachate that contaminates the soil, surface water, groundwater, and also contribute to air pollution [2].
Leachate composition varies widely and among which ammonia-nitrogen (NH$_3$-N) is known for its toxicity effect, especially when it is exist in high concentration. Generally, in old landfill leachate, the organic matter is well stabilized [3], hence the treatment of leachate with high concentration of NH$_3$-N by biological systems is ineffective for such effluents and could be failed. In addition, biological treatment required chemical additives to provide alkaline condition for nitrification processes.

Chemical and physical methods are usually applied prior biological method. The major chemical treatment used for leachate treatment includes coagulation-flocculation, chemical or electrochemical oxidation [4, 5]. Meanwhile, the major physical methods used for landfill leachate treatment are adsorption, membrane filtration, sedimentation and air stripping [6]. Aerobic, anaerobic and anoxic processes are the major biological methods used in combination for treating landfill leachate [7]. However, air stripping is favored over other methods for ammonia removal due to few advantages such as low treatment cost, ability of volatile compounds stripping, and degasification of ammonia at high level concentrations [8, 9].

Air stripping is a mass transfer operation involving the transfer of dissolved substances in water from liquid phase to gas phase by physical action. In air stripping process, volatile organic chemicals is removed from aqueous solution by providing maximum contact between the liquid and air in a specifically designed column. An equilibrium state is reached when these two phases are brought into contact. The off-gas or treated air could be released to the atmosphere or being recovered from the air into a strong acid such as sulphuric acid as subsequent treatment [10, 11]. The amount of ammonia-nitrogen (NH$_3$-N) removed from a liquid in ammonia stripping reactor systems depend on several factors such as NH$_3$-N concentration, pH, temperature, air-to-liquid ratio, water and ambient air temperature, stripping column high, contact time /stripping time, characteristics of the volatile material (partial pressure, Henry’s constant, gas transfer resistance, etc.), turbulence in gases and liquid phases, types of packing materials and the surface area-to-volume ratio [9, 11, 12].

To date, very limited data available on the treatment of scheduled waste leachate is available [13, 14, 15]. The main objective of this work was to investigate the effects of dilution on NH$_3$-N removal efficiency and to compare the effectiveness of raw and diluted leachate treatment by using lab-scale ammonia stripping reactor. The RSM was used for the optimal experimental design of ammonia stripping process. Both raw and diluted leachate was subjected to aerobic chemical and physical treatment by ammonia stripping reactor at different air-liquid ratio, hydrated lime [$\text{Ca(OH)}_2$] dosage, types of packing materials and packing heights. Design-Expert software was used in this study to produce 3D surface responses of quadratic model and to evaluate the interactive relationships between independent variables and response. For each 3D surface plot, one variable was kept constant, while the other two were varied within the experimental ranges.

2. Materials and method

2.1. Leachate sampling and characterization

Leachate samples were taken from a scheduled waste landfill facility. The collection and preservation of sample was done based on Standard Methods for the Examination of Water and Wastewater [16]. The sample was characterized immediately in the laboratory. Table 1 presents the characteristics of raw and diluted leachate samples of the Scheduled Waste Landfill (SWL).
2.2 Ammonia stripping

A 2.5 L diluted (diluted 1:1 with water) and raw leachates were used in each experiment. Hydrated lime (Ca(OH)$_2$) was applied to leachate prior ammonia stripping at different dosage to enhance ammonia and other pollutants removal [13, 14, 15]. The stripping reactor consisted of a 1.20 m (H) x 0.5m (D) column with compressed air introduced at the bottom. Leachate flow rate was maintained at 0.1 L min$^{-1}$, while the air flow rate varied at 2, 5 and 8 L min$^{-1}$. The stripping reactor was operated on a batch mode. Each experiment was carried out for 12 hours with sample withdrawn and analysed on hourly basis. Figure 1 shows the schematic diagram of an ammonia stripping reactor where the leachate was carried up to the top of the column using a dosing pump with perforated PVC distribution plate.

Table 1. Characteristics of raw and diluted leachate from SWL

| Parameter | Units | Raw Leachate | Diluted Leachate |
|-----------|-------|--------------|------------------|
| pH        | -     | 9.25-9.36    | 9.12-9.31        | 9.18             |
| BOD$_5$   | mgL$^{-1}$ | 1610 - 2670 | NA              | NA               |
| COD       | mgL$^{-1}$ | 3430 - 4610 | 1283-1650       | 1319             |
| TSS       | mgL$^{-1}$ | 0 - 870     | NA              | NA               |
| Phosphate | mgL$^{-1}$ | 61-71.4    | 65              | 61-65.5          | 62.8             |
| Colour    | Pt-Co | 2654-2890   | 1988-2220       | 2126             |
| Total Iron| mgL$^{-1}$ | 0.24-0.41  | 0.23-0.37       | 0.28             |
| Turbidity | NTU  | 206-212     | 52.7-59.4       | 55.1             |
| NH$_3$-N  | mgL$^{-1}$ | 1790 - 2570 | 1020-1587       | 1267             |

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![Figure 1. The schematic diagram of an ammonia stripping reactor.](image-url)
2.3 Experimental Design and Mathematical Modelling

The Design Expert Software (version 7.0) was used for the statistical design of experiments and data analysis. The central composite design (CCD) of response surface methodology (RSM) was applied to optimize the four operating parameters and their ranges; air-liquid ratio of 20, 60 and 80, Ca(OH)₂ dosage of 4, 5 and 6 gL⁻¹, with three different types of packing materials (polyurethane foam, polyurethane nylon and non-woven polyester) and packing height of 20, 40 and 60 cm.

The CCD for 30 factorial designs with six additional experimental trials was used as the replicates of the central point to get a good estimate of the experimental error. The coded values for air-liquid ratio (X₁), Ca(OH)₂ dosage (X₂), types of packing materials (X₃), and packing height (X₄), were considered at three levels, assigned as -1 (minimum), 0 (central), and +1 (maximum), respectively. Experimental results are shown as removal efficiency (%) of NH₃-N. Analysis of variance (ANOVA) was used for graphical analyses of the data to attain the interaction between the process variables and the responses. The interactive effects of the independent variables on the dependent variables were illustrated by three- and two-dimensional contour plots. From the 3D plots, the simultaneous interaction of the two factors on the responses was studied. The optimum region was also identified based on the main parameters in the overlay plot.

3. Results and Discussion

3.1 ANOVA

The process performance of ammonia stripping was evaluated by analysing the experimental results of all the terms of coded factors were represented by the following Equation 1:

\[
Y_{\text{NH3-N}} = 55.35 + 8.57X_1 - 2.29X_2 + 10.28X_3 + 4.11X_4 - 1.22X_1X_2 + 0.81X_1X_3 + 3.89X_1X_4 - 3.73X_2X_3 + 3.48X_2X_4 + 5.41X_3X_4 + 10.03X_1^2 + 4.33X_2^2 + 2.70X_3^2 + 2.25X_4^2
\]  

The optimal conditions for NH₃-N removal efficiency were selected based on responses. The final second-order polynomial regression in obtained at 70, 6 gL⁻¹, 60 cm and type 3 (non-woven polyester) for air–liquid ratio, Ca(OH)₂ dosage, packing height and types of packing material, respectively. The adequacy of the response surface models were validated statistically by ANOVA. Table 2 presents the ANOVA of regression parameters of the predicted response surface quadratic model for NH₃-N removal efficiency which showed that the model was significant (p<0.0001) for ammonia stripping process. Table 2 demonstrates that all the variables contributing to the model were significant at the 5% confidence level. The optimal points of working conditions and predicted NH₃-N removal efficiencies were in good agreement between the experimental and predicted with the R²=0.9943.
Table 2. ANOVA for response surface quadratic model for ammonia stripping

|                      | Sum of square | df | Mean square | F-value | Prob>F |
|----------------------|---------------|----|-------------|---------|--------|
| Model                | 5051.24       | 14 | 360.80      | 187.20  | < 0.0001|
| X₁                   | 1323.38       | 1  | 1323.38     | 686.64  | < 0.0001|
| X₂                   | 93.98         | 1  | 93.98       | 48.76   | < 0.0001|
| X₃                   | 1902.01       | 1  | 1902.01     | 986.86  | < 0.0001|
| X₄                   | 304.55        | 1  | 304.55      | 158.02  | < 0.0001|
| X₁²                  | 260.60        | 1  | 260.60      | 135.21  | < 0.0001|
| X₂²                  | 48.49         | 1  | 48.49       | 25.16   | 0.0002  |
| X₃²                  | 18.83         | 1  | 18.83       | 9.77    | 0.0069  |
| X₄²                  | 13.13         | 1  | 13.13       | 6.81    | 0.0197  |
| X₁ X₂                | 23.99         | 1  | 23.99       | 12.44   | 0.0030  |
| X₁ X₃                | 10.48         | 1  | 10.48       | 5.44    | 0.0340  |
| X₁ X₄                | 242.50        | 1  | 242.50      | 125.82  | < 0.0001|
| X₂ X₃                | 222.08        | 1  | 222.08      | 115.23  | < 0.0001|
| X₂ X₄                | 193.42        | 1  | 193.42      | 100.36  | < 0.0001|
| X₃ X₄                | 468.61        | 1  | 468.61      | 243.14  | < 0.0001|
| Residual             | 28.91         | 15 | 1.93        |         |        |
| Lack of fit          | 23.88         | 10 | 2.39        | 2.38    | 0.1760  |
| Pure Error           | 5.03          | 5  |             |         |        |
| Cor Total            | 5080.15       | 29 |             |         |        |
| Std. Dev.            | 1.39          |    |             | R²      | 0.9943  |
| Mean                 | 54.89         |    |             | Adj R²  | 0.9890  |
| C.V%                 | 2.53          |    |             | Pred R² | 0.9707  |
| Press                | 148.98        |    |             |         | 58.972  |

3.2. Effects of operational parameters on removal efficiency

Figure 2 to Figure 7 shows the effect of air–liquid ratio, Ca(OH)₂ dosage, packing height and types of packing material on NH₃-N removal efficiency for diluted leachate. NH₃-N removal increased with a rise in air–liquid ratio and packing height. The response surface of NH₃-N removal illustrated that the higher the air-liquid ratio, the higher NH₃-N removal efficiency (Figures 2, 3 and 4). It was observed the maximum NH₃-N removal was at air-liquid ratio 80 and packing height of 60 cm. Lin et al. [17] observed higher ammonia removal efficiency with the higher air-liquid ratio of stripping process. This is because higher air to liquid ratio promotes the transfer of ammonia into the air phase [9, 18].

![Figure 2](image_url) Design-expert plot; response surface plot for NH₃-N removal at different air-liquid ratio and lime dosage.
However, the effect of packing height and types of packing material was more significant than air-liquid ratio and Ca(OH)$_2$ dosage for NH$_3$-N removal in this study. An increased in packing height of stripping reactor results in higher ammonia removal efficiency regardless of packing materials due to increase of contact time between air and liquid [9]. In this study, the maximum packing height (60 cm) showed higher ammonia removal efficiency for diluted leachate (Figures 5 and 6). Alam and Hossain [9] also investigated few types of packing materials including plastic ring, coal, stone chips, and wood chips in which plastic ring was found to be the most efficient for removal of ammonia, with 91.60% removal efficiency. The quality of packing materials had significant effect for stripping column efficiency. Light, easily produced and high surface area of packing materials gave the best performance for ammonia removal in ammonia stripping column. For this study the highest removal efficiency was obtained when packing material Type 3 (non-woven polyester) was used. Experiments with raw leachate also favour packing material Type 3 (non-woven polyester) resulted the highest NH$_3$-N removal efficiency.
Furthermore, NH$_3$-N removal was higher when the hydrated lime (Ca(OH)$_2$) dosage was at 6 gL$^{-1}$ for diluted leachate treatment. A high pH value by the addition of alkaline agents such as lime and sodium hydroxide is crucial to obtain higher ammonia removal through the displacement of ammonium/ammonia equilibrium. In wastewater, ammonium ions (NH$_4^+$) exist in equilibrium with gaseous ammonia (NH$_3$) as in Equation 2 [15, 19]. Hydroxide ion (OH$^-$) from Ca(OH)$_2$ reacts with ammonium ion (NH$_4^+$) in the leachate to form ammonia gas (NH$_3$). Most ammonium ions (NH$_4^+$) are in the form of NH$_3$ at pH 10.5 to 12. Thus, at higher pH, there is greater proportion of nitrogen in the form of gaseous ammonia and more ammonia is stripped off from the liquid. For raw leachate, less Ca(OH)$_2$ dosage was used in the study. The pH of raw leachate was 9.31, whilst 9.18 of diluted leachate. Thus, at lower pH, diluted leachate demands for more OH$^-$ ions to transform NH$_4^+$ ion to NH$_3$. Therefore, more alkaline chemicals are needed to aid ammonia removal in diluted leachate. This theory is in good agreement with the results of this study.

\[
\text{NH}_4^+ + \text{OH}^- \rightleftharpoons \text{NH}_3 + \text{H}_2\text{O}
\]  

(2)
3.3 Process optimization and comparison with raw leachate treatment

The second order polynomial model generated from RSM was used to confirm the validity of the statistical experimental strategies at optimum conditions for air-liquid ratio, Ca(OH)$_2$ dosage, packing height and types of packing material. When the model was developed from experimental results and checked for adequacy, optimization criteria can be selected to find out the most optimum operating conditions. Based on Table 3, RSM results suggested that the optimal conditions for maximum removal of NH$_3$-N from raw leachate treatment were at air-liquid ratio of 70, Ca(OH)$_2$ dosage of 5 gL$^{-1}$, packing height of 60 cm and types of packing material 3, while for diluted leachate treatment, RSM results suggest the optimal conditions should be at air-liquid ratio of 70, Ca(OH)$_2$ dosage of 6 gL$^{-1}$, packing height of 60 cm and types of packing material 3 (non-woven polyester). Both raw and diluted leachate treatment suggest the same air-liquid ratio (70), packing height (60 cm) and types of packing material (Type 3: non-woven polyester), except for Ca(OH)$_2$ dosage, in which diluted leachate required more dosage compared to raw leachate treatment. It was estimated that based on optimum operating conditions, the maximum value for NH$_3$-N removal via air stripping was estimated as 78% and 81% for raw leachate treatment and diluted leachate treatment, respectively, after 8 hours. To validate this, verification experiments were carried out thrice based on predicted RSM. The selected combinations of the four variables resulted in 76% NH$_3$-N removal for raw leachate treatment and 80% NH$_3$-N removal after 8 hours. Prolonged treatment up to 12 hours successfully obtained 88% of NH$_3$-N removal efficiency and 92% for raw and diluted leachate treatment, respectively. In addition, for raw leachate treatment, 55%, 38% and 49% of turbidity, colour and P-reactive were successfully removed, respectively. For diluted leachate, the removal efficiency for turbidity, colour and P-reactive were 98%, 99% and 98%, respectively, after 12 hours.

The results obtained in this study were relatively similar to other studies, despite different type of sample used. Campos et al. [20] treated the same amount of leachate samples (2.5 L) and after 7 hours of treatment, 91% of ammonia was successfully removed. Nevertheless, high temperature of 60 °C was required to enhance the ammonia removal in their study. In the long term, the requirement of high temperature significantly increases the usage of electricity, which consequently increase the treatment cost. Therefore, low-cost and simple mechanical or air stripping process is chosen over other methods. In addition, previous studies by Cheung et al. [21] documented high ammonia removal efficiency about 93% and >99.5% for 1,600 (24 h). Meanwhile, 88% of NH$_3$-N was removed from raw leachate in this study which accounted about 1767 mg L$^{-1}$ (influent = 2019 mg L$^{-1}$, effluent= 252 mg L$^{-1}$) within 12 hours. As for diluted leachate, about 98% of NH$_3$-N removal efficiency was obtained within 12
hours, which accounted about 1182 mg L\(^{-1}\) (influent = 1280 mg L\(^{-1}\), effluent= 98 mg L\(^{-1}\)). In terms of NH\(_3\)-N concentration removal, direct treatment using raw leachate was better as higher NH\(_3\)-N concentration can be reduced with less dosage required.

The treatment using ammonia stripping reactor in this study seems promising as high strength wastewater with larger volume and high NH\(_3\)-N concentration varied from 1020 – 2570 mg L\(^{-1}\) could be reduced within a short time (12 hours). Compared to Marttinen et al. [6] study, 24 hours was required to treat smaller volume and low-strength leachate (74–220 mg L\(^{-1}\)), with relatively similar ammonia removal efficiency. Since the final effluent for raw and diluted leachate were 252 and 98 mg L\(^{-1}\), respectively, and still not meet the permissible limit standard of NH\(_3\)-N (20 mg L\(^{-1}\)) and pH 9 as stated in Environmental Quality (Industrial Effluent or Mixed Effluent) Regulations 2009, Fifth Schedule (Standard B) [22], the effluent should be further treated with biological method. Biological method can take place efficiently as the concentration of final effluent is low and suitable for biological methods to take place until the discharged requirement was achieved.

4. Conclusion

In this study, ammonia stripping for scheduled waste landfill leachate treatment with and without dilution was investigated. Ammonia stripping process optimization concentrated on the influence of operating parameters such as air-liquid ratio, Ca(OH)\(_2\) dosage, packing materials and packing height using CCD of RSM. All interactions among the variables were evaluated by RSM. The multiple correlation of determination R\(^2\) was found to be 0.9943, which was near to 1 showing that the actual data was well fitted with predicted data. The optimum results obtained from the model indicated that air liquid ratio of 70, Ca(OH)\(_2\) dosage of 6 g L\(^{-1}\), packing height of 60 cm and types of packing material type 3 (non-woven polyester) were required to achieve 88% and 92% of NH\(_3\)-N removal efficiency for contact time of 8 hours and 12 hours, respectively. According to the obtained result, diluted leachate required more Ca(OH)\(_2\) dosage (6 g L\(^{-1}\)) compared to raw leachate which required only 5 g L\(^{-1}\). For other pollutants removal, treatment with diluted leachate is far better as the removal efficiency is much higher when diluted leachate was used compared to raw leachate. It can be concluded from the study that using diluted leachate for ammonia stripping reactor is better to achieved higher NH\(_3\)-N, turbidity, colour and P-reactive removal efficiency. Nevertheless, the optimum conditions for efficient NH\(_3\)-N removal and operating parameters that would make the technology economically viable should be further studied.

Table 3. The optimum parameters and NH\(_3\)-N, turbidity, colour and P-reactive removal efficiency for raw and diluted leachate treatment

| Types of leachate treatment | Ca(OH)\(_2\) dosage (g L\(^{-1}\)) | Average initial concentration (mg L\(^{-1}\)) | Average final concentration (mg L\(^{-1}\)) | RSM (%) | Turbidity removal efficiency (%) | Colour removal efficiency (%) | P-reactive removal efficiency (%) |
|-----------------------------|-----------------------------------|---------------------------------------------|---------------------------------------------|---------|--------------------------------|-------------------------------|----------------------------------|
| Raw leachate                | 5                                 | 2019                                        | 493                                         | 76 (8 hour) | 78                              | 30                            | 34                              | 46                              |
|                             |                                   | 2019                                        | 252                                         | 88 (12 hour) | 55                              | 38                            | 38                              | 49                              |
| Diluted Leachate            | 6                                 | 1280                                        | 262                                         | 80 (8 hour) | 81                              | 97                            | 88                              | 93                              |
|                             |                                   | 1280                                        | 98                                          | 92 (12 hour) | 98                              | 98                            | 98                              | 98                              |
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References

[1] Ngoc U N and Schnitzer H 2009 Waste Manage. 29 1982–1995
[2] Mohd Dinie M S and Mashitah M D 2013 J. Teknol. 62 (1) 95–101
[3] Baig S, Coulomb I, Courant P and Liechti P 1999 Ozone Sci. Eng. 21(1) 1-22
[4] Chiang L, Chang J and Chung C 2001 Environ. Eng. Sci. 18(6) 369-378
[5] Ahn D H, Yun-Chul C and Won-Seok C 2002 J. Environ. Sci. Health A. Tox. Hazard. Subst. Environ. Eng. 37(2) 163-173
[6] Marttinen S K, Kettunen R H, Sormunen K M, Soimasuo R M and Rintala J A 2002 Chemosphere 46 851-858
[7] Im J, Woo H, Choi M, Han K and Kim C 2001 Water Res. 35 (10) 2403-2410
[8] Budzianowski W and Koziol A 2005 Chem. Eng. Res. Des. 83 196–204
[9] Alam R and Hossain M D 2009 J. Water Resource Prot. 1 (3) 210-215 doi: 10.4236/jwarp.2009.13026
[10] Wang G, Mu Y and Yu H Q 2005 Biochem. Eng. J. 23 175-184
[11] Abdullahi M E, Hassan M A A, Noor Z Z and Raja Ibrahim R K 2014 Rev. Chem. Eng. 30(5) 431–451
[12] Hossini H, Rezaee A, Ayati B and Mahvi A H 2016 Health Scope 5 (1) e26479 doi: 10.17795/jhealthscope-26479
[13] Sani A, Rashid M, Nurul Hanira M L and Hasfalina C M 2014 J. Teknol. 68 (5) 25-28
[14] Hanira, N M L, Hasfalina C M, Sani A and Rashid M 2015 AIP Conf. Proc. 1660 090010-1–090010-8 doi: 10.1063/1.4915854
[15] Hanira, N M L, Hasfalina C M, Sani A and Rashid M 2017 J. Teknol. 79 (1) 107–118
[16] APHA 2005 Standard Methods for the Examination of Water and Wastewater American Public Health Association
[17] Lin M, Zhao Z, Cui F, Wang Y and Xia S 2012 Desalin. Water Treat. 40 215-223
[18] Montgomery J M 1985 Water treatment principles & design Consulting Engineers Inc. pp. 237–261 John Wiley & Sons, New York
[19] Muniz C and Roberts P V 1989 Water Res. 23 (5) 589-601
[20] Campos J C, Moura D, Costa A P, Yokoyama L, Araujo F V F, Cammarota M C and Cardillo L 2013 J. Environ. Sci. Health A 48 1105–1113
[21] Cheung K C, Chu L M and Wong M H 1997 Water, Air Soil Poll. 94 209-221
[22] Laws of Malaysia Environmental Quality Act and Regulations (20th ed.) 2010 Kuala Lumpur: MDC Publishers Sdn. Bhd.