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# Statistical analysis of thermal and nonthermal effects of sequential microwave/aeration process for the removal of ammonia from aqueous solution

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ABSTRACT

The application of microwave (MW) radiation followed by aeration (A) for ammonia removal from synthetic solutions was investigated in this study. Results confirmed that the sequential microwave/aeration process was an effective approach for removal of ammonia from aqueous systems. Maximum ammonia removal of 81.7% for 100 mL synthetic solution was achieved by applying 650 W microwave radiation (50% of the maximum MW power output) over 120-s MW irradiation time followed by 10-minute aeration. One-way ANOVA tests and *t*-tests were conducted for the analysis of the differences in ammonia removal efficiencies among different methods. Among the three main contributions for the ammonia removal for the sequential microwave/aeration process (thermal effect, electromagnetic field (EMF) generated by MW radiation, and aeration process), the contribution of the EMF becomes increasingly significant with the increase of MW radiation time, except at a pH of 10. Under the optimum operation condition, the contribution of thermal process, EMF, and aeration was 39, 28, and 33%, respectively.

*Keywords:* Ammonia; Microwave; Aeration; ANOVA; *t*-test; Thermal; Nonthermal

## 1. Introduction

As one of the major inorganic pollutants in surface water, total ammonia nitrogen (TAN) can exist in liquid phase either in an unionized form ($NH_3$) or an ionized form ($NH_4^+$) depending on the pH and temperature [1,2]. Ammonia nitrogen is toxic to aquatic organisms even at low levels. According to the United States Environmental Protection Agency (USEPA), at a pH of 7 and a water temperature of 20°C, the acute and chronic criterion values are 17 and 1.9 mg TAN/L, respectively [3]. Moreover, the increased nitrogen level in water bodies can cause water eutrophication and proliferation of toxic algae blooms in rivers, lakes, and coastal waters [4]. However, for wastewaters with high ammonia nitrogen concentrations such as those produced from the petroleum, textile, fertilizer industries, or landfill leachate, high concentrations of ammonia could inhibit microbial activities [5]. Studies have shown that ammonia is the most toxic substance with inhibition effects on microbial activities, including nitrification [5,6]. It can inhibit the $NO_2$-N oxidation process at an $NH_4$-N concentration of 20 mg/L and can inhibit the $NH_4$-N oxidation process at a concentration of 100 mg/L [6]. Liu et al. [7] reported that ammonia

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inhibition could occur in the range of 1,500–3,000 mg/L as TAN in biological anaerobic processes. Thus, it is necessary to pretreat ammonia-rich wastewater before applying biological processes to improve treatment efficiency.

Conventional methods for ammonia removal from aqueous solutions include biological treatment, air stripping, ion exchange, and adsorption [8]. Biological processes incorporate nitrification and denitrification. However, these processes do not perform well at high ammonia concentrations [9]. For highly contaminated wastewaters such as landfill leachate, ammonia removal is usually achieved by a combination of physical, chemical, and biological processes. This is because high ammonia concentrations are commonly accompanied by high concentrations of organic matter and heavy metals, which make it difficult to obtain satisfactory treatment results using only one method [10–12].

Previous research showed that the ammonia stripping was the most common physical–chemical method for ammonia removal from both ammonia-rich wastewater and landfill leachate [13]. It was able to remove up to 93% ammonia from leachates with high initial ammonia concentration of 5,000–7,000 mg N/L [14]. Ammonia stripping is usually carried out under high pH levels for the removal of ammonia from aqueous systems where most ammonia is in the form of free ammonia. Ammonium hydroxide ($NH_4OH$) is formed as an intermediate product in the reaction at pH between 10 and 11 [15]. Initial heating could enhance the ammonia removal rate during the air-stripping process [16]. However, the high ammonia removal is usually achieved with relatively long contact periods up to 8,000 min [16,17].

Microwave (MW) radiation could provide rapid heating of materials depending on the dissipation factor of the material and has been recently used in wastewater and sludge treatment [18–20]. For wastewater treatment, previous researches were mostly focused on the MW-enhanced oxidation process. Research studies conducted with different oxidants such as sodium persulfate, ozone, and hydrogen peroxide reported that the application of MW can result in the increased removal efficiencies of the total organic carbon (TOC) and chemical oxygen demand (COD) while applying a MW radiation process without oxidants, the removal of TOC and COD were not significant [18,21,22]. MW radiation reduced TAN in waters with TAN concentrations in the ranges of 25–5,000 mg/L [23,24]. Both Lin [24] and Rabah and Darwish [23] reported pH 11 as the optimum MW radiation operation condition for ammonia removal from aqueous systems. The ammonia removal efficiency slightly increased with the increase of initial TAN concentration. When the pH of the wastewater was adjusted to around 11, the removal of TAN increased with radiation time to approximately 100% in a laboratory batch scale [24] and 80% in a pilot scale [25].

Lin et al. [24] applied MW and aeration simultaneously to a synthetic solution with initial TAN concentration of 500 mg/L and pH of 11. When applying 350 W microwave radiation, the ammonia removal efficiency achieved approximately 40% before reaching the boiling point of 100˚C. The remaining portion of the dissipated ammonia was removed in the following two minutes after the solution reached the boiling point, by a combination of MW and thermal processes. It was observed that when the aeration process was applied concurrently with the MW radiation process, the contribution of aeration decreased with longer radiation time.

However, the continuous boiling process employed by Lin et al. [24] could be a safety concern due to the high operation temperatures and the possible generation of unknown secondary pollutants when applied to real landfill leachate. Moreover, when MW radiation has been used as a pretreatment approach, the high effluent temperature can have a negative effect on the subsequent biological treatment processes.

As a pretreatment process, MW radiation process under high pH levels could reduce ammonia significantly with negligible organic compound removal [24]. This can maintain sufficient COD supply as the carbon source for the sequential biological removal process.

The main objective of this research was to evaluate the MW radiation followed by an aeration process for removal of ammonia from aqueous solutions under different pH and temperature. Statistical analysis was used to determine the contribution of the thermal and nonthermal effects of MW radiation approaches with and without an aeration process. For both safety and economic concerns, the samples were maintained below the boiling point.

## 2. Material and methodology

As a sequential microwave/aeration process, aeration was applied immediately after the MW radiation process. Traditional heating using water bath (WB) with and without aeration was applied to determine the contribution of the thermal effect during the both MW and microwave/aeration process. Preliminary tests were carried out to find optimum pH and aeration levels.

Four sets of experiments were conducted: WB, microwave (MW), sequential microwave/aeration

process (MW + A), and sequential water bath/aeration process (WB + A). For each test, 100 mL of synthetic solution was used. All the tests were conducted with three replicates in batch mode. For both economic and safety concerns, the synthetic solution samples were maintained below the boiling point.

### 2.1. Material and equipment

In this study, synthetic solution which contained 2,700 mg/L TAN was prepared by dissolving ammonia chloride in distilled water. For each test, 100 mL of the fresh synthetic solution was prepared. The initial pH was around 5.7. The pH was adjusted to the desired value using 10 mol/L NaOH. The MW process was carried out by a Panasonic microwave oven (Model NN-S 750) with an operating frequency of 2,450 MHz. The maximum power output was 1,300 W and could be adjusted from 10 to 100% in 10% intervals.

The aeration process was performed using a Model 200 MARINA pump with a total aeration rate of 110 L/h with 2 air diffusers. In each test, only one diffuser was placed in the batch reactor. For the tests carried out with the synthetic solution, a 150-mL beaker was used as the batch reactor for all MW with and without aeration processes.

TNT 832 ammonia vials from Hach Company were used to test ammonia concentrations based on the salicylate method using a HACH DR5000 Spectrophotometer. The 10 mg/L ammonia nitrogen standard solution from HACH Company was used to calibrate the spectrophotometer. The pH was measured using a glass electrode in combination with a Fisher Accumet® Model XL25 dual channel pH/ion meter [26].

### 2.2. Preliminary tests

Two sets of preliminary tests were carried out to find optimum pH and aeration levels. The first one, a MW radiation power output of 60% and MW radiation time of 100 s were used with subsequent aeration time ranging from 5 to 15 min in 5-min intervals. The purpose was to find the optimum aeration time. pH was adjusted to 11 in this set. In the second set of preliminary test, a MW radiation power output of 50% of the maximum MW radiation power output, MW radiation time of 120 s, and 10 min aeration was used under pH ranging from 8 to 12 with 1 pH unit interval. The purpose was to identify the optimum pH.

### 2.3. Experimental design

To determine the thermal and nonthermal contributions during the ammonia removal process using microwave radiation followed by aeration, four different sets of experiments were conducted: WB, microwave (MW), sequential microwave/aeration process (MW + A), and sequential water bath/aeration process (WB + A). These were further divided into the following categories:

(1) MW with and without aeration process using synthetic solution at two MW output levels of 50 and 100% of the maximum power output for different irradiation time under three pH levels of 10, 10.5, and 11.
(2) WB with and without aeration process using synthetic solution at different temperature under three pH levels of 10, 10.5, and 11.

The details of the experimental design for WB are shown in Table 1.

For the MW and MW + A tests, when using 50% of the maximum MW output, the radiation periods investigated were 30/60/90/120 s. The temperature of the sample was controlled to remain below the boiling point. The temperatures shown in Table 2 for WB and WB + A tests were selected in such a way to match the temperatures measured in MW and MW + A tests when using 50% power output for comparison purposes. Based on the results of preliminary tests, for all the MW + A and WB + A tests, the aeration time was selected at 10 min.

The general experimental flow diagram is shown in Fig. 1. For each test, 100 ml of synthetic solution was used. For the MW tests, the pH was adjusted to the desired level using 10 mol/L NaOH solution and then the batch reactor was treated by microwave radiation for the desired time period, exposed to 50% of the maximum MW power output. The sample temperature was measured immediately after the MW process. Distilled water was used to compensate the water loss after MW process. One mL of the radiated sample was taken after the adjustment for the first ammonia measurement. Then, the sample was aerated for 10 min, immediately after the first measurement. Water loss was compensated again by distilled water

Table 1
Experimental designs of WB + A processes for the synthetic solution

| WB temperature (℃) | | 65 | 85 | 95 |
|---|---|---|---|---|
| pH | 10 | ✓ | ✓ | ✓ |
| | 10.5 | ✓ | ✓ | ✓ |
| | 11 | ✓ | ✓ | ✓ |

Table 2
MW time (s) when using 50% of the maximum output and the corresponding rater bath temperature (℃)

| Microwave irradiation time (s) | Water bath temperature (℃) |
|---|---|
| 60 | 65 |
| 90 | 85 |
| 120 | 95 |

after the aeration process as well. The second measurement was taken after the second adjustment.

For the WB test, the WB tub was heated to 5℃ higher than the temperature obtained from the microwave process. The WB required a significantly longer period of time (>120 s) to equalize the temperature between the sample and the WB. This increased heating period would result in higher recorded removal efficiency, altering the outcome of the experiment. The sample temperature was constantly monitored to make sure the same temperature level was reached for the MW and WB process. The water adjustment and sampling process was identical to the MW process. The aeration process was applied after the first sampling process. Water loss was compensated again after the aeration process. The second measurement was taken after the second adjustment.

### 2.4. Statistical methods

One-way ANOVA tests were performed to determine whether significant differences ($p < 0.05$) existed among the ammonia removal efficiencies of the four different treatment methods with different MW radiation or WB thermal levels. When the ANOVA test showed a significant difference among all groups of data, several *t*-tests ($p < 0.05$) were carried out for paired groups of data for further analysis.

## 3. Results and discussion

### 3.1. Results of preliminary tests

The ammonia removal efficiency was calculated by the following (Eq. (1)):

$$\text{Ammonia removal efficiency} = \frac{C_1 - C_0}{C_0} \times 100\,\% \quad (1)$$

where $C_1$ is the TAN concentration after treatment, $C_0$ is the initial TAN concentration.

The results of preliminary tests for the determination of optimum aeration time are shown in Fig. 2. The ammonia removal rate rose as the aeration time increased from 0 to 15 min. However, after 10 min, the increase in ammonia removal efficiency was negligible. For economic reasons, extending the aeration time beyond 10 min is not a cost-effective design. Thus, 10 min was chosen as the optimum aeration time and used for subsequent experiments.

The results of preliminary tests for the determination of optimum pH are shown in Fig. 3. Ammonia removal efficiency increased sharply with pH until pH of 10.5 and dropped off after 10.5. Therefore, pH levels of 10, 10.5, and 11 were selected to be investigated in the following tests.

### 3.2. Effect of pH

All four sets of WB, MW, MW + A, and WB + A tests were conducted at three different pH levels. As

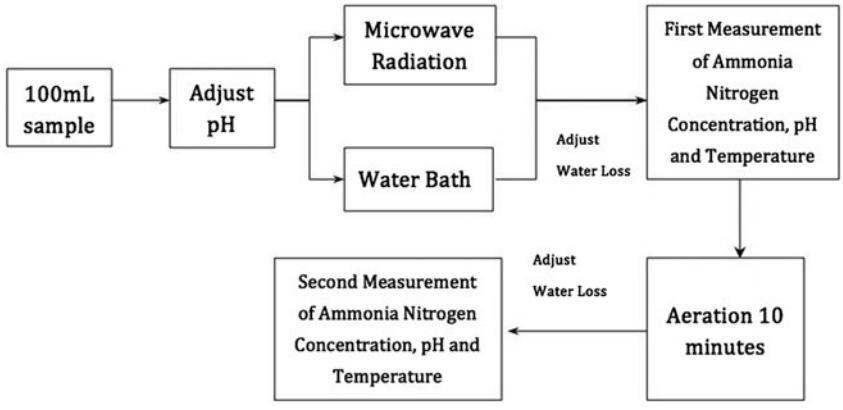


Fig. 1. Experimental flowchart.

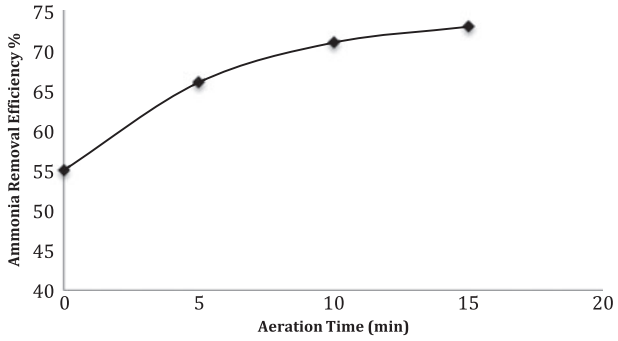


Fig. 2. Preliminary test result of aeration time, using pH 11, 60% of the maximum microwave output, 100 s of radiation time.

can be seen from Fig. 4, the general trend observed was that the ammonia removal efficiencies increased with the increase of pH from 10 to 10.5 and then increased or dropped as pH increased further to 11 for all three MW radiation (WB temperature) levels. For example, in Fig. 4(c), when high MW radiation time of 120 s was applied, for both MW and M + A process, the ammonia removal efficiencies obtained at pH of 10.5 and 11 were relatively similar, but significantly higher than the values of pH 10. The WB and WB + A test results with high temperature levels of 95°C showed the same trend. As such, it seems a pH of 10.5 is the optimum pH. The same trend was obtained in the combined MW and aeration conducted by Lin et al. [24].

The increase of ammonia removal efficiency with increasing pH could be explained by the equilibrium distribution between $NH_3$ and $NH_4^+$, which is heavily dependent on the pH value and temperature of the aqueous solution. The percentage of $NH_3$ and $NH_4^+$

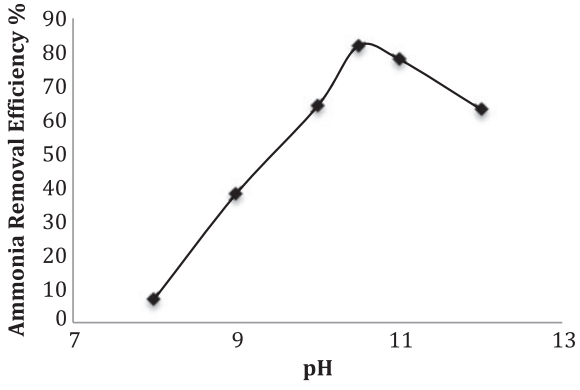


Fig. 3. Preliminary test result of pH, using 50% of the maximum MW power output, 120-s MW radiation time, and the aeration time was 10 min.

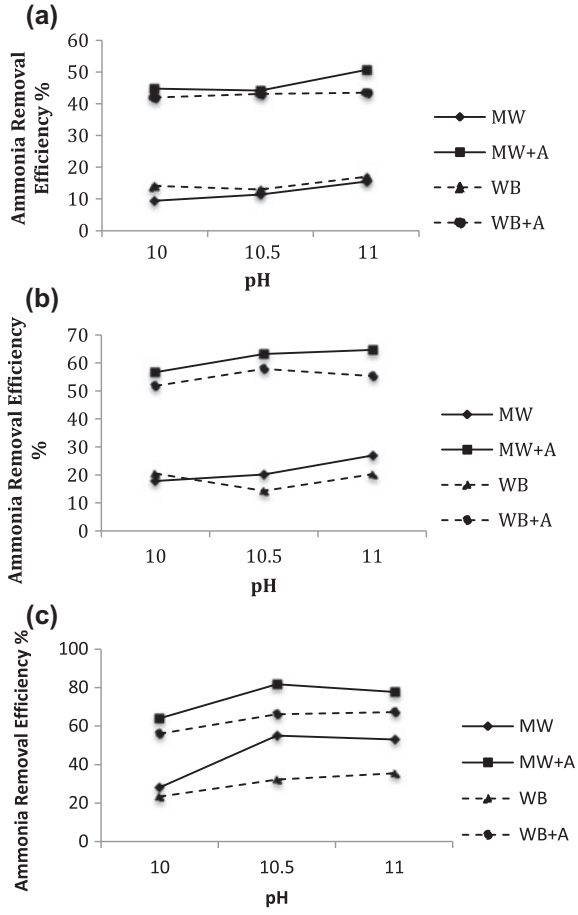


Fig. 4. Ammonia removal rate with MW and M + A at three different radiation time levels: (a) 60 s, (b) 90 s, and (c) 120 s. WB and WB + A with the same finial temperature levels: (a) 65°C, (b) 85°C, and (c) 95°C.

can be derived by the following equation containing the acid ionization constant, $K_a$, as shown in (Eq. (2)):

$$\frac{[NH_3][H^+]}{[NH_4^+]} = K_a \tag{2}$$

where $[NH_3]$ is the concentration of $NH_3$, and $[NH_4^+]$ stands for the concentration of $NH_4^+$. $[H^+]$ is the concentration of $H^+$ (pH). $K_a$ is the acid ionization constant, which changes with respect to temperature. The $pK_a$ (acid dissociation constant at logarithmic scale) value at this temperature is approximately 9.2, which means that at pH 9.2, the ratio of $NH_3$ to $NH_4^+$ is about 1:1 [25]. For pH values lower than 7, the majority of ammonia exists as $NH_4^+$. At low pH conditions, the concentration of un-ionized ammonia is negligible. As pH increases over 7, the concentration of $NH_3$ rises and it becomes the dominant form.

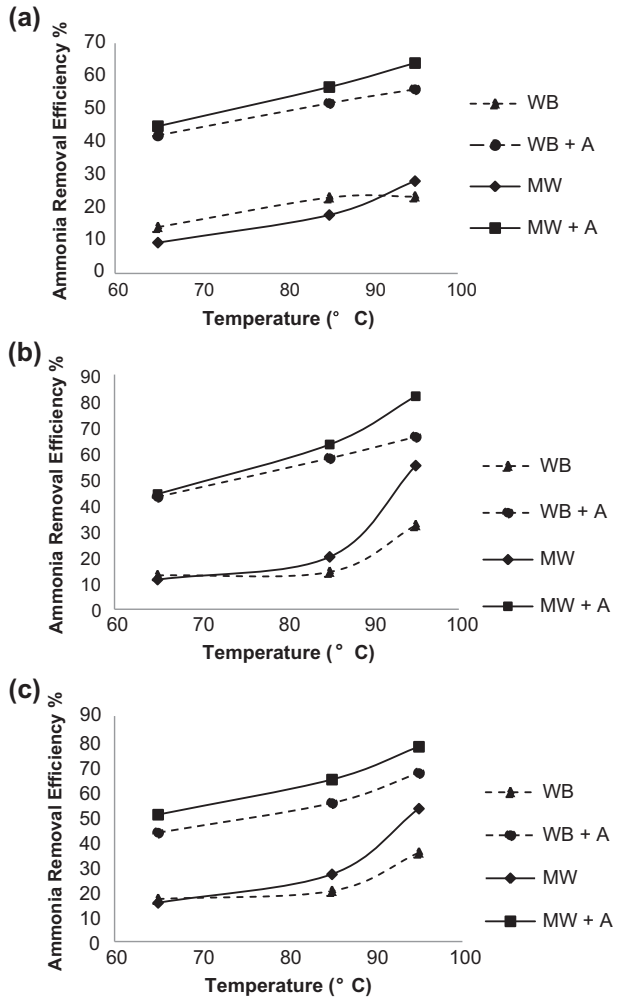


Fig. 5. Ammonia removal using WB and WB + A (MW and MW + A) processes with three finial temperature levels: 65, 85, and 95°C (corresponding MW irradiation time levels: 60 s, 90 s, and 120 s) under pH of (a) 10, (b) 10.5, and (c) 11.

### 3.3. Effect of temperature

The ammonia removal results for WB, WB + A, MW, and MW + A as a function of temperature at pH of 10, 10.5, and 11 are shown in Fig. 5. For the MW and MW + A methods, both thermal and nonthermal effects exist during the ammonia removal process. There are three main contributing factors to the ammonia removal for the MW + A process: the thermal effect (increased temperature), the electromagnetic field (EMF) generated by MW radiation, and the aeration process. Therefore, WB and WB + A tests were conducted as controls to determine the effect of temperature and EMF for the MW and MW + A processes.

Fig. 5 shows that the removal efficiencies of all four different methods increased with time (and temperature). This is in agreement with previous research [23,25]. For the shortest MW radiation time (60 s), the differences in ammonia removal efficiencies between the MW/WB processes and the corresponding processes with aeration were not significant under all three pH levels. For tests with longer radiation time, the ammonia removal efficiencies obtained from test involving the MW process were higher than those using WB with the exception of those conducted under pH level of 10. This can be explained by Henry's law, which expresses that the gas solubility of an aqueous system decreases with the increase of temperature. The excess volatile $NH_3$ would dissipate from the aqueous solution. The high temperature also increases the molecular movement for both water and $NH_3$. More ammonia nitrogen would leave the system during the heating process in the form of volatile ammonia nitrogen gas ($NH_3$) than at lower temperatures due to the increased kinetic energy.

### 3.4. Effect of microwave radiation

As shown in Fig. 5, when the shortest MW radiation period of 60 s was applied, the contribution of the thermal process to ammonia removal was quite significant, but decreased as the MW radiation time increased. The contribution of the EMF became significant at high MW radiation levels (temperature) with the exception at a pH level of 10. The contributions of the EMF during the MW and MW + A test showed a similar trend as the operational pH of 10.5 and 11.

The ANOVA test result for all data (ammonia removal efficiencies) collected from different methods under different MW radiation time or WB temperature at pH of 10.5 is shown in Table 3. Similar trends were

Table 3
Single factor ANOVA test among all collected data

| Source of variation | SS | df | MS | *F* | *p*-value | *F* cr. |
|---|---|---|---|---|---|---|
| Between groups | 17,890.91 | 11 | 1626.45 | 129.18 | 1.40E-18 | 2.22 |
| Within groups | 302.18 | 24 | 12.59 | | | |
| Total | 18,193.09 | 35 | | | | |

Table 4
One-way ANOVA tests for four methods (MW, MW + A, WB, and WB + A) under three different MW radiation periods (WB temperature): (a) 60 s (65˚C), (b) 90 s (85˚C), and (c) 120 s (95˚C)

| Source of variation | SS | df | MS | *F* | *p*-value | *F* cr. |
|---|---|---|---|---|---|---|
| (a) Between groups | 2,920.79 | 3 | 973.60 | 94.68 | 0.00 | 4.35 |
| Within groups | 71.98 | 7 | 10.28 | | | |
| Total | 2,992.77 | 10 | | | | |
| (b) Between groups | 5,068.74 | 3 | 1,689.58 | 215.42 | 0.00 | 4.35 |
| Within groups | 54.90 | 7 | 7.84 | | | |
| Total | 5,123.65 | 10 | | | | |
| (c) Between groups | 3,898.38 | 3 | 1,299.46 | 85.38 | 0.00 | 4.07 |
| Within groups | 121.77 | 8 | 15.22 | | | |
| Total | 4,020.14 | 11 | | | | |

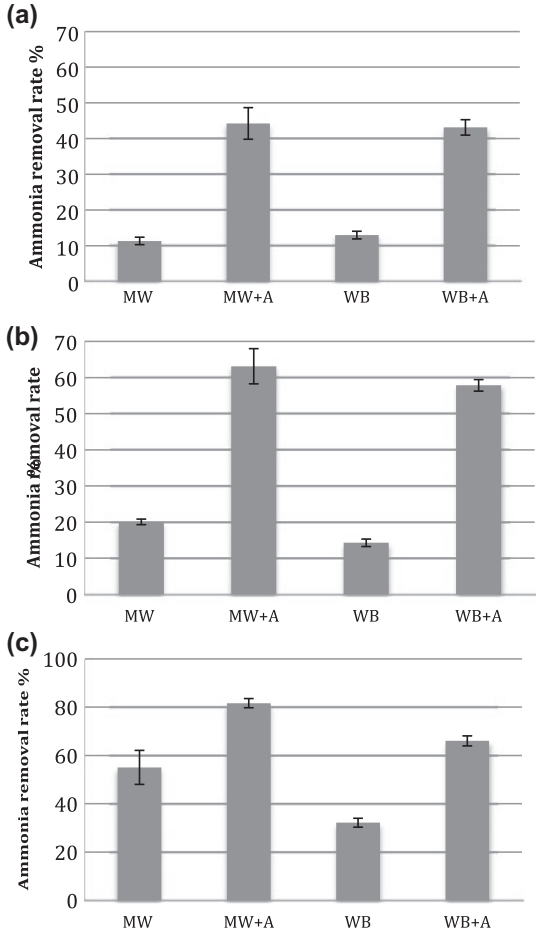


Fig. 6. Ammonia removal using MW and MW + A (WB and WB + A) processes with three MW irradiation time (WB temperature) levels: (a) 60 s (65˚C), (b) 90 s (85˚C), and (c) 120 s (95˚C).

observed for other pH values with the exception of pH 10 with MW (WB) only; however, to avoid repetition and limit the number of figures, only tests results from pH 10.5 are presented and discussed below. According to the ANOVA test (Table 3), the *p*-value was 1.40E-18, which is lower than 0.05, indicating there were significant differences between the removal efficiencies using different treatment methods and/or conditions.

One-way ANOVA tests for four methods (MW, MW + A, WB, and WB + A) for each MW radiation period or corresponding final temperature levels were conducted to investigate whether the removal efficiencies of each methods are significantly different within one MW radiation power level and the corresponding WB temperature level. As shown in Table 4, the *p*-values for all three one-way ANOVA tests are 0.00, indicating that there are significant differences between methods within one MW radiation power level and the corresponding WB temperature level.

Fig. 6 shows the ammonia removal efficiencies of different methods at three different MW radiation periods or corresponding final temperature levels. *t*-tests were performed based on Two-Sample Assuming Unequal Variance; Results are shown in Table 5. For the *t*-test of both MW vs. WB and MW + A vs. WB + A, when under low radiation time (60 s) and temperature (65˚C), the *p*-values were larger than 0.05, which showed that there was no significant difference between them. Thus, the contribution of the EMF generated by microwave is not significant at low radiation levels. For the same two sets of *t*-test, under high radiation time (120 s) and temperature (95˚C), the *p*-value was lower than 0.05, indicating that the contribution of the EMF under high radiation level was significant.

Table 5
*t*-test results for different treatment methods under three different MW radiation time (WB temperature): (a) 60 s (65℃), (b) 90 s (85℃), and (c) 120 s (95℃)

| | MW | WB | MW + A | WB + A | MW | MW + A | WB | WB + A |
|---|---|---|---|---|---|---|---|---|
| (a) Mean | 11.40 | 13.00 | 44.20 | 45.20 | 11.40 | 44.20 | 13.00 | 45.20 |
| Variance | 1.09 | 1.17 | 19.60 | 14.80 | 1.09 | 19.60 | 1.17 | 14.80 |
| Observations | 3.00 | 2.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.00 | 3.00 |
| Hypothesized mean difference | 0.00 | | 0.00 | | 0.00 | | 0.00 | |
| df | 2.00 | | 4.00 | | 2.00 | | 2.00 | |
| *t* Stat | −1.67 | | −0.27 | | −12.50 | | −13.70 | |
| P (*T* <= *t*) two-tail | 0.24 | | 0.80 | | 0.01 | | 0.01 | |
| *t* Critical two-tail | 4.30 | | 2.78 | | 4.30 | | 4.30 | |
| (b) Mean | 20.10 | 14.30 | 63.20 | 58.80 | 20.10 | 63.20 | 14.30 | 57.90 |
| Variance | 0.60 | 1.07 | 23.80 | 0.07 | 0.60 | 23.80 | 1.07 | 2.55 |
| Observations | 3.00 | 2.00 | 3.00 | 2.00 | 3.00 | 3.00 | 2.00 | 3.00 |
| Hypothesized mean difference | 0.00 | | 0.00 | | 0.00 | | 0.00 | |
| df | 2.00 | | 2.00 | | 2.00 | | 3.00 | |
| *t* Stat | 6.75 | | 1.55 | | −15.10 | | −37.00 | |
| *P*(*T* <= *t*) two-tail | 0.02 | | 0.26 | | 0.00 | | 0.00 | |
| *t* Critical two-tail | 4.30 | | 4.30 | | 4.30 | | 3.18 | |
| (c) Mean | 55.10 | 32.20 | 81.70 | 66.10 | 55.10 | 81.70 | 32.20 | 66.10 |
| Variance | 49.60 | 3.39 | 3.62 | 4.29 | 49.60 | 3.62 | 3.39 | 4.29 |
| Observations | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Hypothesized mean difference | 0.00 | | 0.00 | | 0.00 | | 0.00 | |
| df | 2.00 | | 4.00 | | 2.00 | | 4.00 | |
| *t* Stat | 5.47 | | 9.63 | | −6.31 | | −21.20 | |
| *P*(*T* <= *t*) two-tail | 0.03 | | 0.00 | | 0.02 | | 0.00 | |
| *t* Critical two-tail | 4.30 | | 2.78 | | 4.30 | | 2.78 | |

The contribution of EMF can be explained by the characteristic and heating mechanism of the MW. MWs are a type of electromagnetic wave, with a frequency range from 300 MHz to 300 GHz. When applying MW radiation to a material, it causes polarized chains of molecules to align with the direction of the electrical field and make the dipoles change their orientation in phase with the EMF at high rotating speeds. However, the intermolecular bonds restrict the movements between the dipoles, causing the delay of rotation. This resistance converts part of the radiation energy into heat [27].

When applying microwaves to a conductor, the radiation can be reflected from the surface of the material such as in the case of metals. Insulators are transparent to microwave radiation: the radiation can pass directly through the material without interference. The third type is lossy material, which can adsorb the microwave radiation. The energy that is dissipated in the material turns into heat. The ammonia aqueous solution is a lossy material that adsorbs microwave energy. The heating mechanism of the microwave is dipole polarization: the dipoles are rotating under the EMF created by the microwave radiation. In this case, both $NH_3$ and water molecules are dipoles. During this dipole rotation under the radiation process, the molecular bonds between the $NH_3$ and water molecules are weakened, which makes it easier for the ammonia molecules to leave the aqueous system. Thus, during the microwave radiation process, some $NH_3$ is dissipated through thermal processes (increased temperature); the rest escapes the system as a result of the weaker molecular bounds and increased molecular movement caused by the EMF.

### 3.5. Effect of aeration

For both WB + A and MW + A processes, all tests were carried out immediately after the WB or MW test. To determine the effect of aeration, tests were carried out without microwave or WB processes. A total of 100 mL synthetic solution was adjusted to a pH of 10.5 first and then aerated for 10 min. At room temperature (25℃), the ammonia nitrogen removal efficiency was about 20% during this treatment process.

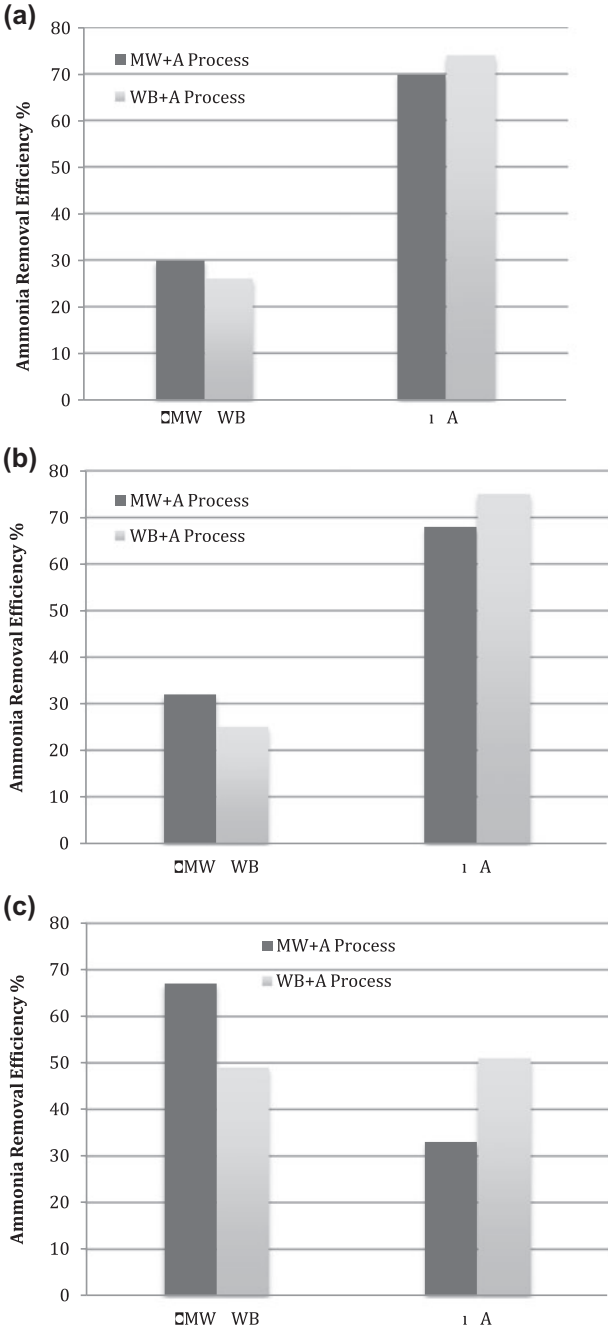


Fig. 7. Contribution of MW WB and aeration (A) during the MW + A and WB + A process under MW different radiation time (WB temperature) (a) 60 s (65˚C), (b) 90 s (85˚C), and (c) 120 s (95˚C).

According to Fig. 7, at low radiation time periods, most of the ammonia was removed due to the aeration process. For the 60 s MW + A process, 74% of the total removal was due to the aeration process. For the 65˚C WB + A process, 70% of the total ammonia removal was a result of the aeration process. At low radiation time periods, the contribution from aeration of the MW + A and WB + A process was almost identical. For the MW + A process, at the longest irradiation period (120 s), only 33% of the total ammonia removal was due to the aeration process, which is significantly lower than the value at 60 s. For the WB + A process, when the final temperature was 95˚C, the contribution of the aeration process was 51%. The aeration process contributed significantly to ammonia removal for both MW + A and WB + A process at lower thermal conditions. With longer radiation time, the contribution of the aeration process decreases relative to the effects of the MW radiation process.

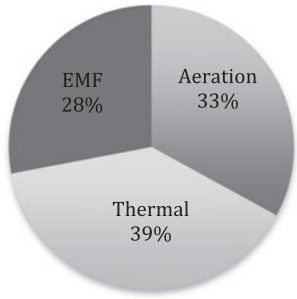


Fig. 8. Contribution of EMF, aeration, and thermal for the MW + A process with the highest removal efficiency achieved at pH of 10.5, with 120-s microwave radiation and 10-min aeration.

For all four methods under different thermal conditions, the MW + A method attained the highest removal efficiency using 120-s radiation time. As shown in Fig. 8, 39% percent of the total ammonia removal was due to the thermal effect, 61% was due to the nonthermal process. The two main nonthermal affects are the aeration and EMF. In previous research, when the aeration was applied during the microwave process, the effects of the aeration process were limited at longer radiation periods [24]. In this study, the contribution of aeration was 33% when reaching the maximum ammonia removal efficiency.

## 4. Conclusion

The thermal and nonthermal effects of the MW + A process for removal of ammonia from the aqueous solution were investigated. Four different ammonia removal methods (MW, MW + A, WB, and WB + A) were used to specify the effect of thermal and nonthermal process. The conclusions are as follows:

(1) There was significant removal of ammonia nitrogen during the sequential microwave/aeration process. For 100 mL synthetic solution, the maximum removal efficiency of 81.7% was achieved at pH 10.5; by applying 650 W microwave radiation (50% of the maximum MW power output) over 120-s MW irradiation time followed by 10-min aeration.
(2) Under the optimum removal conditions, 39% of the total ammonia removed was a result of the thermal processes, while 61% of the total ammonia removal was from nonthermal (aeration and EMF) processes. The contributions of aeration and EMF were 33 and 28%, respectively, at maximum ammonia removal conditions.
(3) At a pH of 10 during the shortest irradiation periods, the EMF contribution to total ammonia removal was negligible. As the MW radiation power level and irradiation period was increased, the contribution of microwave EMF also increased correspondingly, ultimately accounting for approximately 28% of the total ammonia removal during the MW + A process.

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