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HRT EFFECT ON SIMULTANEOUS COD, AMMONIA AND MANGANESE REMOVAL FROM DRINKING WATER TREATMENT SYSTEM USING A BIOLOGICAL AERATED FILTER (BAF)

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Abstract

Three different hydraulic retention times (HRTs) were investigated for $\text{NH}_4^+\text{-N}$ and Mn^{2+} removal using an upflow biological aerated system (BAF) as a new approach in drinking water treatment system. Currently in Malaysia, there is no specific treatment for $\text{NH}_4^+\text{-N}$ and Mn^{2+} in drinking water treatment plant. BAF is a well known system in biological treatment for wastewater but not for drinking water treatment. This study showed that at 24 hours operation of BAF system, about 91.3% of COD, 94.4% of $\text{NH}_4^+\text{-N}$ and 83.4% of Mn^{2+} were efficiently removed. When HRT was decreased to 12 and 6 hours, there was insignificant removal difference in COD and $\text{NH}_4^+\text{-N}$ removal. Instead, the Mn^{2+} removal significantly showed an increasing trend ($p < 0.05$) as the HRT was decreased with the removal percentages of 92.1% (12 hours) and 94.8% (6 hours). Real-time monitoring through pH, ORP and DO profiles confirmed that completed simultaneous $\text{NH}_4^+\text{-N}$ and Mn^{2+} removal occurred within 6 to 7 hours HRT.

Keywords: BAF system, biofilm, drinking water treatment, HRT, simultaneous ammonia and manganese removal

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1. Introduction

Water contamination by ammonia ($\text{NH}_4^+\text{-N}$) is worldwide problem, especially for developing countries such Malaysia, India, China, Russia and Chile. In Malaysian rivers, especially around the state of Selangor, the $\text{NH}_4^+\text{-N}$ contamination in rivers was a major problem for drinking water treatment plants (DWTPs), while manganese (Mn^{2+}) is a minor contaminant (Hasan et al., 2011a). From year 2004 to 2012, water treatment plants were shut down for certain period of times due to high levels of $\text{NH}_4^+\text{-N}$ over 6 mg/L, which exceeded the regulated standard limit for raw water. Water contamination by $\text{NH}_4^+\text{-N}$ was reported to reach a maximum of 20.3 mg/L and the minimum was 2.6 mg/L.

Contamination of raw water by $\text{NH}_4^+\text{-N}$ is due to the proximity of the intake point for the water treatment plant to a nearby landfill area and also due to sewage wastewater being released to the rivers. High levels of $\text{NH}_4^+\text{-N}$ in raw water are also due to other factors such as industries, and agricultural activities which are located adjacent to the rivers. In addition, wastes from these activities as well as domestic wastes, sewage, latex and leachate which were not properly treated are directly released to the rivers (Hasan et al., 2011a). Moreover, the increasing $\text{NH}_4^+\text{-N}$ concentration in raw water is also influenced by illegal industries and garbage disposal along the rivers. Due to high levels of $\text{NH}_4^+\text{-N}$ in the raw water, the DWTPs were frequently shutdown because the

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conventional DWTPs do not have to remove $\text{NH}_4^+\text{-N}$. Although $\text{NH}_4^+\text{-N}$ and Mn^{2+} can be removed physical-chemically or biologically from drinking water, green technology of biological treatment is preferable due to no requirement for extra chemicals, no production of hazardous by-products and the volume of the regenerated sludge is appreciably smaller and hence, it is easier to be handled (Aslan and Simsek, 2017; Tekerlekopoulou and Vayenas, 2007). Further, the Malaysian Ministry of Energy, Green Technology and Water are now promoting use of green technology in order to conserve the natural environment and resources, which minimize and reduces the negative impact of human activities.

Currently, biological treatment for drinking water is not worldwide applied for simultaneous removal of $\text{NH}_4^+\text{-N}$ and Mn^{2+} . Several European countries such as France, Germany and Netherlands and also Asian countries like Japan have applied biological processes to remove nutrients (e.g. ammonia, nitrite, nitrate and phosphate) in treated water in order to obtain biologically stable water and hence limit the growth rate of microorganisms in distribution pipes and reservoirs (van der Kooij, 1995). Several researchers had investigated the performance of biological processes for drinking water treatment (Kasuga et al., 2010; Zhang et al., 2010). Zhang et al. (2010) applied biofilter for semivolatile organic compounds removal, while Yu et al. (2007) used biofilters to remove nitrogen ($\text{NH}_4^+\text{-N}$, $\text{NO}_2\text{-N}$) from drinking water.

In this study, advanced biological treatment of Biological Aerated Filter (BAF) system is proposed and studied as an additional system for simultaneous treatment of $\text{NH}_4^+\text{-N}$ and Mn^{2+} from DWTPs. The current typical Malaysian DWTPs, that include aeration, coagulation and flocculation, sedimentation, filtration, and chlorination process, did not have feasibility to treat raw water containing high levels of $\text{NH}_4^+\text{-N}$ and Mn^{2+} . The BAF system is well known as one of biological treatment methods in wastewater treatment but not in drinking water treatment. The system showed a good performance for drinking water treatment as obtained in previous studies (Hasan et al., 2010a, 2011b, 2013).

In drinking water treatment application, Tian et al. (2009) found that 89% of $\text{NH}_4^+\text{-N}$ was removed by membrane bioreactor (MBR) with HRT of 0.5 hours, compared to biological activated carbon (BAC) with 54.5% removal. Meanwhile, in wastewater treatment, Lee et al. (1998) reported that, COD and $\text{NH}_4^+\text{-N}$ were successfully removed at HRT of 4 to 10 hours, with respective removals of 90.5-97.5% and 72.9-94.4 %. Instead of many studies of HRT effect on $\text{NH}_4^+\text{-N}$ removal, the information about the biological Mn^{2+} removal that focuses on the effect of HRT is limited. Moreover, there is also lacking information regarding simultaneous removal of $\text{NH}_4^+\text{-N}$ and Mn^{2+} in a single stage treatment.

Generally, it is difficult to achieve good simultaneous removal of $\text{NH}_4^+\text{-N}$ and Mn^{2+} in single stage treatment. This is due to factors like oxidation-

reduction potential requirement (ORP), dissolved oxygen (DO) and pH conditions. When drinking water contains $\text{NH}_4^+\text{-N}$, the biological removal of Mn^{2+} will only take place after the $\text{NH}_4^+\text{-N}$ being removed completely, due to the necessary evolution of the redox potential. It means that longer HRT is required to achieve higher effluent quality of $\text{NH}_4^+\text{-N}$ and Mn^{2+} . This requirement leads to time-consuming and more expensive conditions to operate and maintain the relevant reactor. Thus, the aim of this study is to investigate the most suitable HRT for effective simultaneous removal of $\text{NH}_4^+\text{-N}$ and Mn^{2+} using a BAF system.

2. Material and methods

2.1. BAF description and operation

A lab-scale upflow BAF system was designed as shown in Fig. 1. Details material, dimension and configuration of the BAF system has been published in our previous work (Hasan et al., 2015). The sampling ports (SP) were set-up along the height of BAF column at 20 cm intervals in order to allow water and biomass samplings. The characteristics of the plastic media are listed in Table 1. The floating media type was selected because it had a large surface area that is more suitable for microbial attachment and enhancement.

Table 1. Characteristics of plastic media

| <i>Characteristics</i> | <i>Dimension</i> |
|-----------------------------|------------------|
| Diameter, D (mm) | 16 |
| Height, H (mm) | 10 |
| Weight (g) | 0.65 |
| Density (kg/m^3) | 888 |

A peristaltic pump (Masterflex, USA) drove the direct upflow of synthetic water through the BAF column from an influent tank at a flow rate of 580 mL/min to occupy the BAF column in about 30 minutes, with influent entering from the bottom BAF. A compressor (PUMA XN2040, Taiwan) provided aeration with a flow rate in the range of 100-150 mL/min for sufficient dissolved oxygen (DO). In order to ensure the homogeneity of air distribution and transfer, air diffuser was used and located at the bottom of the BAF column. Meanwhile, the excessive accumulated biomass on the media was removed by performing backwash process. This step can prevent the BAF column from clogging and to maintain the microbial activity inside.

The operating conditions were carried out with three different HRTs of 24, 12 and 6 hours with respective organic loading rates (OLRs), $\text{NH}_4^+\text{-N}$ loading rates (NLRs) and Mn^{2+} loading rates (MLRs) as listed in Table 2. The treatment was operated in a batch mode with initial HRT of 24 hours, then decreased to 12 and finally to 6 hours. For each HRT, BAF system were performed with 20 (24 hours), 16 (12 hours) and 18 (6 hours) identical runs with total period of operation about 2 months.

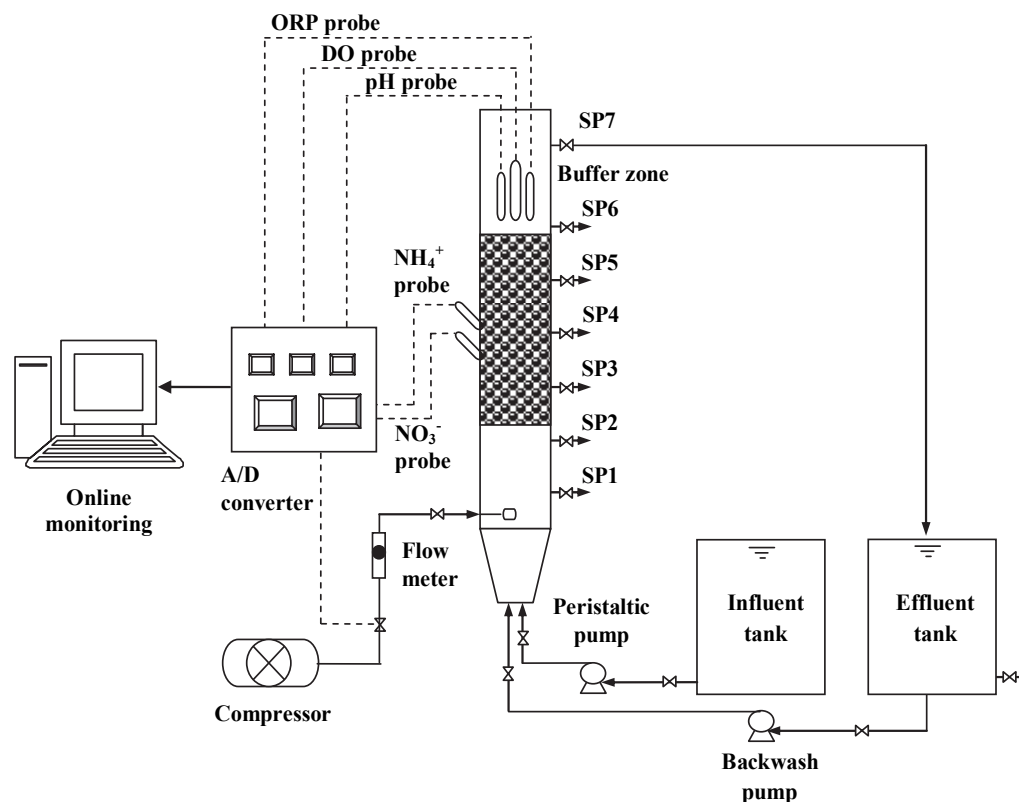


Fig. 1. Schematic diagram of the biological aerated filter (BAF) system

Table 2. Treatment operating conditions of simultaneous COD, NH₄⁺-N and Mn²⁺ removal

| HRT (hours) | Run period (d) | OLR (kg COD/m ³ .d) | NLR (kg NH ₄ ⁺ -N/m ³ .d) | MLR (kg Mn ²⁺ /m ³ .d) |
|-------------|----------------|--------------------------------|--|--|
| 24 | 1-10 | 1.0 | 0.01 | 0.002 |
| 12 | 11-18 | 1.6 | 0.02 | 0.003 |
| 6 | 19-27 | 4.0 | 0.04 | 0.008 |

The decreasing trend of HRT was selected based on the COD, NH₄⁺-N and Mn²⁺ removal performances during operation. At initial stage of each run period, pH was maintained in the range of pH 6-7 by adding 100 mg/L of sodium bicarbonate to avoid a lack of alkalinity for nitrifiers growth, while DO was monitored at range of 1-5 mg/L throughout treatment.

2.2. Microbial source

The sewage activated sludge (SAS), used as microbial source in this study was obtained from a sewage treatment plant located in Putrajaya, Malaysia. At start-up, the SAS was acclimatized in the BAF system for 21 days to grow and enhance the microbial on the plastic medium.

The nutrient feed for acclimatization of microbes contained carbon (100 mg/L) for cell synthesis, inorganic nutrients as nitrogen source (5mg/L), phosphorus (2.5 mg/L), and trace elements such magnesium (8 mg/L), iron (0.3 mg/L) and manganese (1.45 mg/L). The removal of COD, NH₄⁺-N and Mn²⁺ during the acclimatization were 84.5%, 95.3% and 91.6%, respectively.

2.3. 16S ribosomal RNA bacterial identification

Bacterial DNA was extracted from a bacterial suspension in nutrient broth cultivated at 37°C for 24 hours. The extraction was conducted using Wizard[®] Genomic DNA Purification Kit (Promega, USA) protocol for isolation of genomic DNA from Gram positive and negative bacteria. Universal primers 27F (AGAGTTTGATCTGGCTCAG) and 1492R (GGTTACCTTGTTACGACTT) were used to amplify 16S rRNA gene according to the PCR amplification protocol provided by Promega Manufacture (USA). The PCR was performed using Mastercycler (Eppendorf S, Eppendorf, Version 3.608). PCR-amplified product was purified by Wizard[®] Plus SV Minipreps DNA

Purification System (Promega, USA). The PCR product was sent to First BASE Laboratories Sdn. Bhd (Kuala Lumpur, Malaysia) for the 16S rRNA sequencing. Finally, the result of 16S rRNA sequence of the isolate was compared with those of other microorganisms by way of BLAST through National Centre for Biotechnology Information homepage.

2.4. Synthetic water

Synthetic water was prepared using a tap water to simulate a contaminated drinking water. The composition of synthetic water consisted of glucose (C₆H₁₂O₆: 105 ± 6 mg/L), ammonium sulphate ((NH₄)₂SO₃: 10 ± 0.2 mg/L), sodium bicarbonate (NaHCO₃: 100 mg/L), magnesium chloride (MgCl₂.6H₂O: 8 mg/L), iron chloride (FeCl₃.6H₂O: 0.3 mg/L), manganese chloride (MnCl₂.4H₂O: 2.0 ± 0.1 mg/L), calcium chloride (CaCl₂.2H₂O: 4.5 mg/L) and potassium dihydrogen phosphate (KH₂PO₄: 2.5 mg/L). All the chemicals used were reagent grade salts (System, Malaysia).

The simulation of the synthetic contaminated drinking water is based on the real contaminations of the pollutant in selected Malaysian rivers (Hasan et al., 2011a). Furthermore, the contamination of NH₄⁺-N in raw water also based on the report from DOE (2010) which NH₄⁺-N contamination at several rivers was reported higher than 10 mg/L.

2.5. Analytical methods

Samples were taken at sampling port 6 (SP6) (Fig. 1) after the end of each HRT and collected in 1 L polypropylene (PP) bottles and then immediately analyzed. The excessive mixed liquor suspended solid (MLSS) was filtered using nitrate cellulose membrane filter, 0.45 µm (Whatman, USA). The COD concentration was determined using digestion method at 150 °C for 2 hours through HACH Reactor Digestion and then was measured using spectrophotometer (HACH DR/2010, USA) at an adsorbance of 620 nm (Method 8000). The ammonium was measured through Nesslerization method (Method 8038) at an absorbance of 425 nm using HACH DR/2010 (USA). Nitrite (NO₂⁻) and nitrate (NO₃⁻) were analyzed through ion chromatography (IC: Model 882 Compact IC Plus, Switzerland). Meanwhile, manganese in the form of Mn²⁺ was detected using the Perkin Elmer Adsorption Atomic Spectrometer (AAnalysat 800, USA). The bacterial biomass was determined by using

gravimetric method, as described in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

2.6. Real-time monitoring and data acquisition

The pH, ORP and DO, were routinely monitored during the experimental period by using pH (Model PD1R1 GLI, USA), ORP (Model PD1R1 GLI, USA) and DO (Model 5400 GLI, USA) probes that were connected to GLI meters (Model 33, USA) for online monitoring purposes. The NH₄⁺ and NO₃⁻ parameters were also measured through Swan sensor ammonium and nitrate ion selective electrodes (ISE) (FAM: Ammonium; FAM: Nitrate, Switzerland). Online monitoring of the pH, DO and ORP was conducted using a computer programming of Microsoft Visual C++ (Version 7.1.3088, Washington, USA) and the data were recorded every 60 second. To provide connection between computer, meters (pH, ORP, DO, NH₄⁺-N and NO₃⁻-N) and air control unit, the A/D converter interface and data acquisition card (EX92026, Taiwan) were installed in the computer.

3. Results and discussion

3.1. COD removal

The COD removal trends at the three HRTs were depicted in Fig. 2. It can be seen that the COD effluent concentrations were not much different at the end of each HRT. The average effluent concentrations were observed as 9.4 mg/L for HRT of 24 hours, 10.1 mg/L for HRT of 12 hours, and 7.6 mg/L for HRT of 6 hours. All the COD effluents have met the MCL of 10 mg/L regulated in NSDWQ (2009) by Ministry of Malaysian Health.

Although the influence of each HRT on the COD removal was not much different, the BAF system showed a good performance at higher OLR of 4.0 kg COD/m³.d (6 hours HRT) compared with lower OLRs of 1.6 kg COD/m³.d (12 hours HRT) and 1.0 kg COD/m³.d (24 hours HRT).

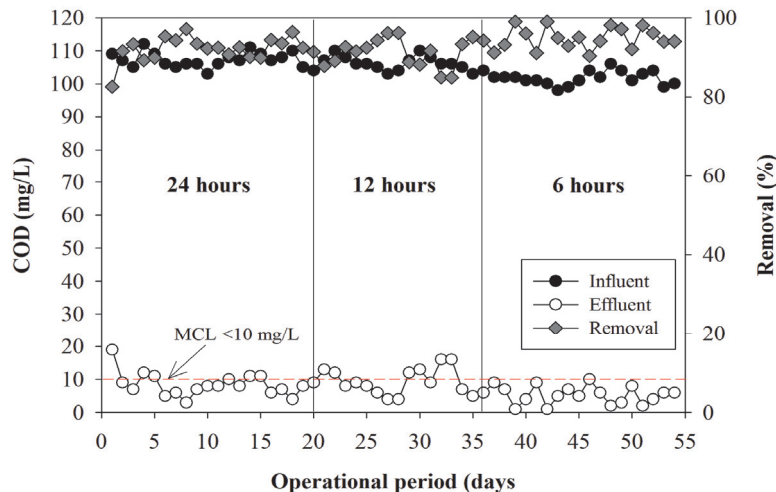


Fig. 2. Trends of COD removal at three different HRTs

As comparison, Wang et al. (2008) used BAF system after ozonation oxidation pretreatment to remove COD from textile washing wastewater and found that COD removal reached 71.8% (effluent of 18.6 mg/L) at HRT of 4 hours under ozone dosage of 45 mg/L.

3.2. NH_4^+ -N removal and formation of NO_x^- -N

As shown in Fig. 3a, the BAF system performed well at a various HRTs for NH_4^+ -N removal, resulting good effluent quality concentrations. The effluent concentrations were below the MCL of 1.5 mg/L that was regulated in NSDWQ (2009). At HRT of 24 hours (day 1-20), the NH_4^+ -N was completely removed with an average effluent concentration of 0.17 mg/L. Meanwhile, at HRT of 12 hours (day 21-36) and 6 hours (day 37-54), the effluent had low concentrations of 0.23 and 0.15 mg/L, respectively. Even low NH_4^+ -N effluent concentrations were achieved at the three HRTs, the BAF performance at HRT of 6 hours is more effective because it can remove high NLR of 0.04 kg NH_4^+ -N /m³.day than those of 24 hours (0.01 kg NH_4^+ -N /m³.day) and 12 hours (0.02 kg NH_4^+ -N /m³.day). The pH value and DO concentrations at the three HRTs

were monitored in respective range of pH 6-7 and 1-5 mg/L.

The formation of NO_x^- -N (total NO_2^- -N + NO_3^- -N) for the three HRTs (Fig. 3b) showed unstable trends with average concentrations for each HRT of 24, 12 and 6 hours as 16.7, 18.9 and 19.2 mg/L, respectively. Since the main focus was on NH_4^+ -N removal, nitrite (NO_2^- -N) and nitrate (NO_3^- -N) were only monitored daily at the end of each HRT. At the end of the treatment period for each HRT, it can be seen that NO_x^- -N formation was lower than total of NO_2^- -N and NO_3^- -N MCL, in which respective MCL regulated by Malaysian for NO_2^- -N and NO_3^- -N were 10 mg/L.

Furthermore, with a fully aerobic operation of BAF system, the conversion of NO_3^- -N to nitrogen gas was inhibited due to oxic conditions. On the other hand, at the end of HRT 24 hours in this study, the remaining organic carbon in the water was only a small amount of 9 mg/L which is not sufficient to perform denitrification process. The heterotrophic bacteria that were responsible in the denitrification process required an anoxic condition with very low DO concentration and also required a sufficient organic carbon supplement as electron donor for nitrate removal (Metcalf and Eddy, 2005).

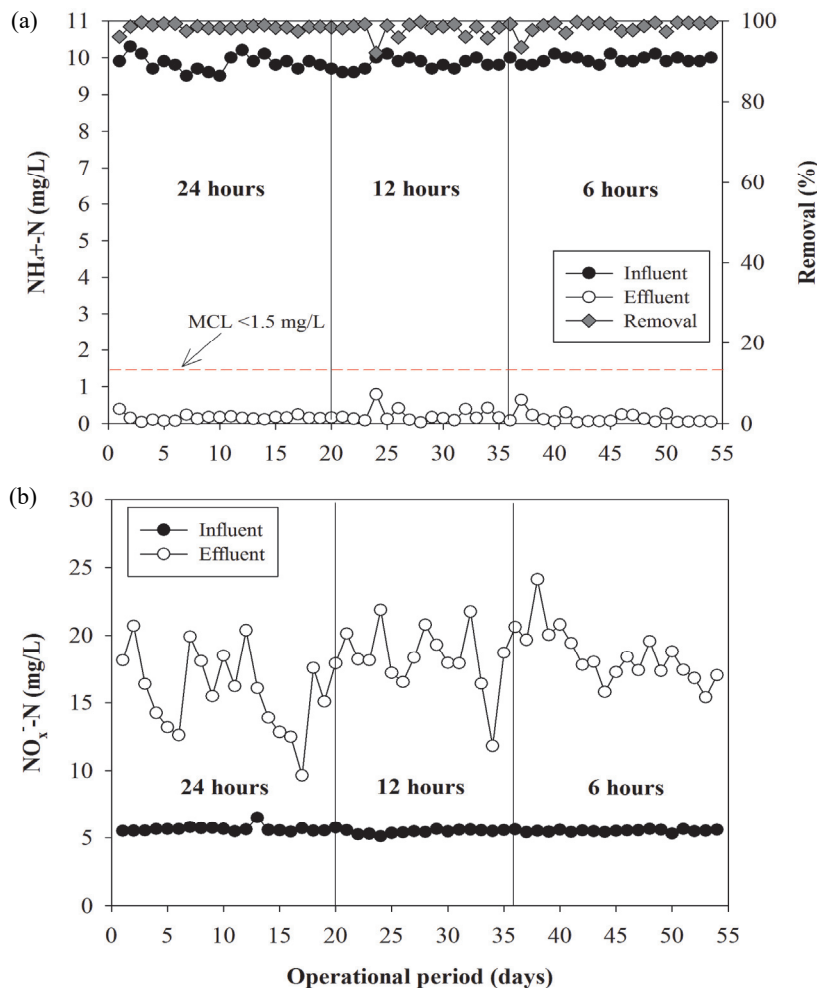


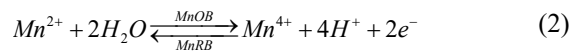
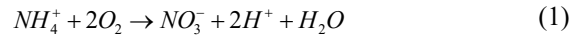
Fig. 3. Trends of (a) NH_4^+ -N removal and (b) NO_x^- -N formation at three different HRTs

3.3. Mn²⁺ removal

As shown in Fig. 4, at HRT of 24 hours and MLR of 0.002 kg Mn²⁺/m³-day, the average effluent concentration of Mn²⁺ was 0.34 mg/L. When the HRT was decreased to 12 (MLR of 0.003 kg Mn²⁺/m³.day) and 6 hours (MLR of 0.008 kg Mn²⁺/m³.day), the removal of Mn²⁺ increased with the remaining concentrations of Mn²⁺ effluent were 0.16 mg/L and 0.10 mg/L, respectively. Isolation and identification of bacteria through 16S rRNA technique, found that there were six dominant bacteria in the microbial community as well as *Bacillus cereus*, *Lysinibacillus sphaericus*, *Microbacterium oxydans*, *Bacillus thuringiensis*, *Staphylococcus* sp. and *Micrococcus luteus*. Investigation through batch experiment on the isolated bacteria using 250 mL conical flasks (Hasan et al., 2010b, 2012a) revealed that *Bacillus cereus* was the most effective bacteria for the removal of Mn²⁺. The occurrence of biotransformation Mn²⁺ to Mn⁴⁺ was due to the presence of manganese-oxidizing bacteria (MnOB) assisted by sufficient DO in water (1-5 mg/L).

From the result, it can be seen that, simultaneous removal of NH₄⁺-N and Mn²⁺ from drinking water occurred using BAF system even though both contaminants have a different of redox evolution. The finding obtained in this study is difference with Mouchet (1992) which found that biological Mn²⁺ removal through bio-oxidation process only occurs after nitrification is complete. Biotransformation of soluble Mn²⁺ to insoluble Mn⁴⁺ is a reverse reaction in a normal environment with the presence of MnOB and manganese reducing-bacteria (MnRB) (Kub, 2003). The identification of MnOB and MnRB of *Bacillus cereus* in the microbial community has proved that manganese oxidation and reduction occurred during treatment. Therefore, higher Mn²⁺ effluent quality at 24 hours HRT could be due to this phenomenon in which Mn⁴⁺ was retransformed to Mn²⁺. Cerrato et al. (2010) and Hasan et al. (2012b)

in their investigation found that isolated *Bacillus* sp. from drinking water treatment as well as *Bacillus cereus* were capable of oxidizing and reducing manganese. Furthermore, as depicted in Fig. 5, pH value at the end of each HRT were in range of pH 6.17-6.62 at 24 hours HRT, 5.97-6.35 at 12 hours HRT and 5.79-6.10 at 6 hours HRT. This shows that lower pH value at 6 hours HRT was due to the formation of hydrogen ions which formed during the simultaneous removal of NH₄⁺-N and Mn²⁺ (Eqs. 1 and 2), causing an acidic condition in the water effluent water.



3.4. Relationships of NH₄⁺-N and Mn²⁺ with pH-ORP-DO

ORP can be used as a tool to indicate oxidation or reduction process in the NH₄⁺-N and Mn²⁺ removal from drinking water. As depicted in Fig. 6, the increment-decrement of ORP trends showed the occurrence of simultaneous oxidation of NH₄⁺-N and Mn²⁺ and reduction of Mn⁴⁺ in the BAF system. The highest ORP of 340 mV was recorded at 6 hours (DO elbow) and decreased to 325 mV at the end of 24 hours, indicating the reduction of Mn⁴⁺ to Mn²⁺ and no more oxidation of NH₄⁺-N. The trends showed that NH₄⁺-N and Mn²⁺ were completely and effectively removed at HRT of 6 hours. This result is in agreement with the work done by Mouchet (1992) that found biological Mn²⁺ oxidation took place when the ORP values were over 300 mV.

The DO elbow and NH₄⁺-N valley were observed at HRT around 6 to 7 hours, indicating completion of nitrification. At this hour, the NH₄⁺-N and Mn²⁺ concentrations were below the Malaysian regulated limit. After 7 hours, it can be seen that the pH increased and ORP decreased, giving evidence that reduction of Mn²⁺ occurred.

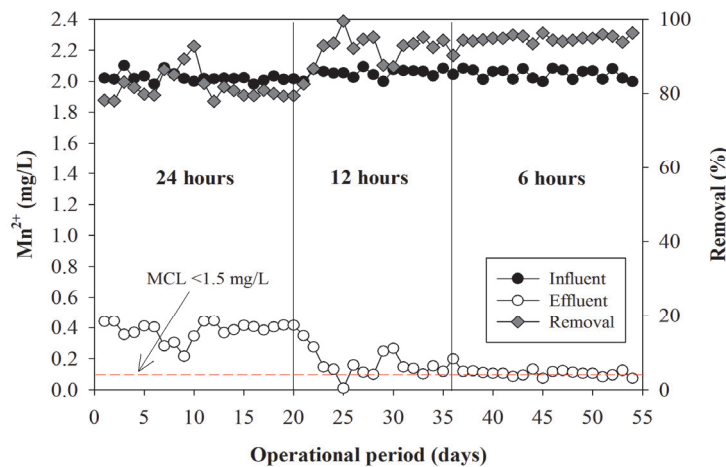


Fig. 4. Mn²⁺ trends at different HRTs

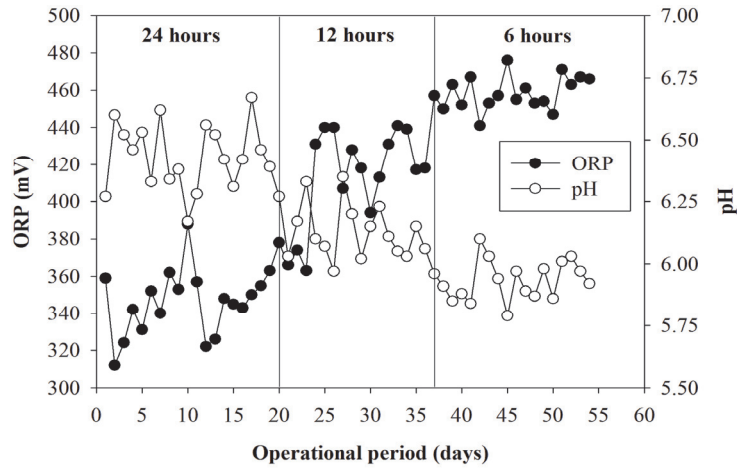


Fig. 5. Variations of pH and ORP

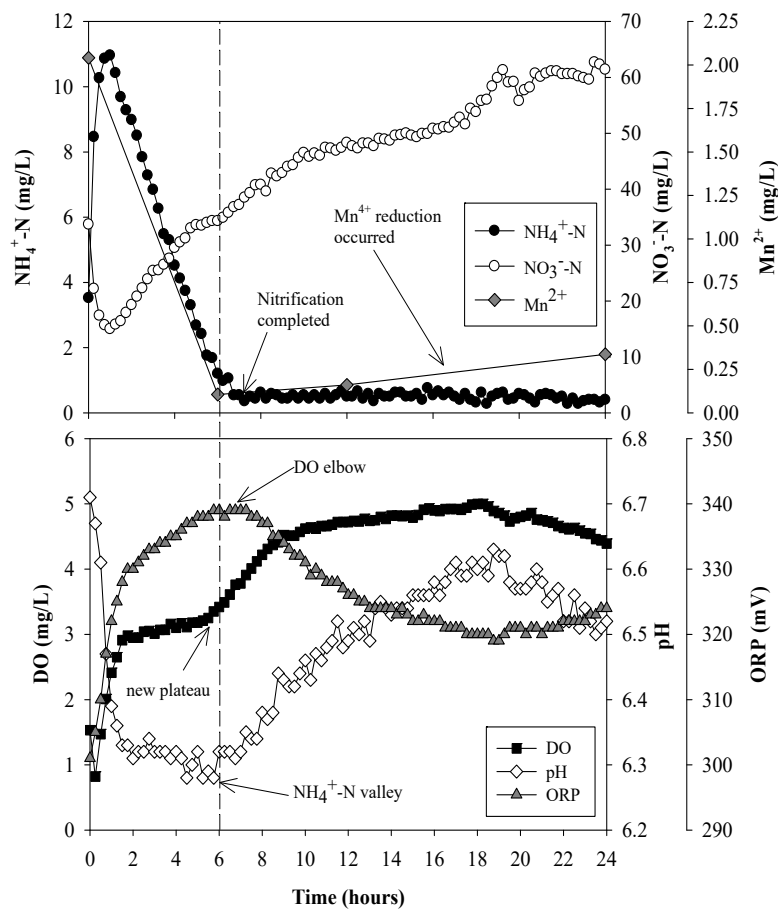


Fig. 6. Real-time monitoring of $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, Mn^{2+} , DO, pH and ORP for 24 hours HRT

Furthermore, from 7 to 24 hours, DO concentration showed a stable trend suggesting no microbial activities in oxygen uptake for biological $\text{NH}_4^+\text{-N}$ and Mn^{2+} oxidation. The lower effluent pH value in this study has given evidence that the simultaneous biological $\text{NH}_4^+\text{-N}$ and Mn^{2+} removal occurred in a single stage treatment using BAF system. The biological removal of Mn^{2+} occurred between pH in range of 6.8 to 7.8 (Tekerekopoulou and Vayenas, 2008). The Mn^{2+} could also be removed at lower pH without requiring any additional chemicals (Mouchet, 1992).

3.5. Overall performances

Table 3 shows the summary of respective overall removal percentages for COD, $\text{NH}_4^+\text{-N}$ and Mn^{2+} at three different HRTs of 24, 12 and 6 hours. The removal percentages for COD and $\text{NH}_4^+\text{-N}$ at the three different HRTs were not much different. The COD removal percentage was higher at HRT of 6 hours with 94.8% with OLR of 4.0 kg COD/m³.d followed by 91.3% for 12 hours and 92.1% for 24 hours. For $\text{NH}_4^+\text{-N}$, the removal was almost 98% for the three HRTs.

Table 3. Summary of overall COD, NH₄⁺-N and Mn²⁺ removals

| HRT (h) | COD removal (%) | | | | NH ₄ removal (%) | | | | Mn removal (%) | | | |
|---------|-----------------|------|---------|--------|-----------------------------|------|---------|--------|----------------|------|---------|--------|
| | min | max | average | stdev | min | max | average | stdev | min | max | average | stdev |
| 6 | 90.4 | 99.0 | 94.8 | 0.0274 | 93.5 | 99.7 | 98.5 | 0.0156 | 93.4 | 96.3 | 94.9 | 0.0084 |
| 12 | 84.9 | 96.2 | 91.3 | 0.0366 | 92.1 | 99.7 | 97.8 | 0.0196 | 82.6 | 99.5 | 91.9 | 0.0414 |
| 24 | 82.6 | 97.2 | 92.1 | 0.0312 | 96.1 | 99.6 | 98.4 | 0.0077 | 77.9 | 89.3 | 81.2 | 0.0302 |

Min: minimum, Max: maximum, Stdev: standard deviation

Hence, the nitrification process was completed at a shorter HRT of 6 hours. However, longer HRT of 24 hours resulted with a decreasing removal percentage of Mn²⁺ with 81.2% removal. Instead, the highest Mn²⁺ removal percentage was achieved at HRT of 6 hours with almost 95% removal.

Statistical one-way analysis of variance (ANOVA) using SPSS (version 16.0, USA) was determined in order to evaluate the significance of the HRT effect on simultaneous COD, NH₄⁺-N and Mn²⁺ removal. When HRT was shortened from 24 to 12 and finally to 6 hours, one-way ANOVA model at the level of 0.05 indicated that the three levels of HRT were not significantly difference for COD (*F*-ratio = 0.32) and NH₄⁺-N (*F*-ratio = 0.24) removal (*p* > 0.05). Instead, there was a significant effect of the HRT on the Mn²⁺ removal with the *F*-ratio of 19.5 (*p* < 0.05). Although there were no significant effect of HRT on COD and NH₄⁺-N, but HRT did effect significantly on Mn²⁺ removal and therefore, a shorter HRT would be the better option for efficient drinking water treatment operation. It is because the shortest HRT for simultaneous NH₄⁺-N and Mn²⁺ removals with good effluent qualities below MCL using BAF system could save the energy consumption for the aeration time, manpower and more water capacity could be treated.

4. Conclusions

A laboratory-scale of an upflow biological aerated filter (BAF) as a new approach in drinking water treatment system was designed in order to treat NH₄⁺-N and Mn²⁺ simultaneously. Among the novelty that obtained in this studies included; Investigation of the three different HRTs on the simultaneous NH₄⁺-N and Mn²⁺ removal had resulted good effluent quality at HRT of 6 h in which both parameters had met the regulated standard. At longer HRT, the BAF executed well for COD and NH₄⁺-N but not for Mn²⁺ (MCL > 0.1 mg/L) in which the oxidized Mn⁴⁺ was reduced back to Mn²⁺ due to the presence of MnRB and H⁺ ions produced. The removal efficiency of COD and NH₄⁺-N was constantly high over 90% and 98%, respectively at the three different HRTs while removal efficiency for Mn²⁺ was only significant at HRT of 6 hours with a removal percentage almost 95%.

Other novelty was a real-time monitoring proved that completed simultaneous NH₄⁺-N and Mn²⁺ biologically oxidation occurred within HRT of 6 to 7 hours. This information is beneficial in future for real-time control strategy development for economically simultaneous NH₄⁺-N and Mn²⁺ removal from drinking water using BAF system.

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