Aerated steel slag filter system performance study for pollutants removal from domestic wastewater

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Abstract. Nitrogen removal from wastewater often requires a highly cost of chemical treatment to prevent over loading of nutrient in effluent discharge to the surface water body. However, to remove nitrogen it requires a complex process. Therefore, the aim of this study is to develop an aerated rock filter (ARF) system design under Malaysia condition. A pilot-scale VFARF with 2.0 m height and 0.3 m diameter and a HFARF with 1.0 m long and 0.3 m wide and 0.5 m height has been developed at Taman Bukit Perdana Wastewater Treatment Plant (WWTP) Batu Pahat, Johor to monitor the performance of the ARFs for nitrogen removal from domestic wastewater. The optimum value of HLR and aeration rate was 2.72 m^3/m^3.day and 10 L/min, respectively. For monitoring the effectiveness of the VFARF and HFARF, influent and effluent twice a week grab samples have been collected and analysed for TKN, Ammonia Nitrogen, BOD_5, COD, TSS, Alkalinity, *E*-coli, pH, Dissolved Oxygen and Temperature. From the study, it was found that the VFARF system has outperformed as the removal efficiency of TKN, AN, TSS, and *E-coli* was 89%±7%, 97%±2%, 86%±17%, and 97%±2%. The removal efficiency was slightly lower in the HFARF as their removal was 78%±11%, 71%± 12%, 88%±15%, and 91%±16% for TKN, AN, TSS, and *E-coli*. However, their performance insignificant in removing organic matter, BOD_5, COD as the removal efficiencies in the VFARF and HFARF were 84%±13%, 65%±23% and 85%±12%, 75%±21%, respectively. Alkalinity, pH and DO profiles for VFARF and HFARF systems effluent values were average at 107.08±28.35 mg/L, 7.14±0.27, 5.20±0.84 mg/L, 147.24±16.20 mg/L, 6.99±0.15 and 3.75±0.37 mg/L, respectively. Temperature value for this VFARF and HFARF system was 31.1±1.1ºC. From monitoring study between VFARF and HFARF, it found that VFARF system was outperformed than the HFARF in removing nitrogen from domestic wastewater.

Keywords: Domestic Wastewater, Horizontal flow aerated rock filter, Hydraulic loading rate, Vertical flow aerated rock filter.

1. Introduction

Nowadays, eutrophication problems in developing countries are related to high nutrient in domestic wastewater discharge. Human activities have accelerated the rate and extent of eutrophication through both point-source discharges and non-point loadings of limiting nutrients, such as nitrogen that contain high ammonia into aquatic ecosystems (i.e., cultural eutrophication), with dramatic consequences for drinking water sources, fisheries, and recreational water bodies as indicated in [1]. Discharge from incomplete treatment of nutrient from wastewater could be the main culprit of the above mentioned problem. However, to remove nitrogen from domestic wastewater with high nutrient using conventional system are expensive due to utilization of chemicals, high operational and maintenance cost, lack of treatment capacity, efficiencies, stability and space requirements [2]. Therefore, the demand of appropriate low-cost technology and an economic effective system are crucial as an improvement to the existing treatment systems for treating high nutrient wastewater and towards the new effluent discharge compliance.

Rock filter system has been invented more than 30 years ago in the US with the main purpose of removing organic matters and algae from wastewater. However, due to the system was rapidly turned to anoxic condition with limited removal of ammonium nitrogen in the system effluent [3]. Therefore, aerated system has been explored to enhance the removal of ammonium nitrogen from domestic wastewater in the UK [4]. Aerated Rock Filter (ARF) emerged as one of the attractive treatment system for nitrogen removal as the system is simple to operate, low operation and maintenance costs, low energy requirements, and overall 'low technology' [5]. However, information on the performance of the ARF under various operating and environmental conditions is still lacking in terms of the impact different organic and HLR [2]. Hence, this study was focused on the ARF system performance monitoring of optimum HLR and aeration rate with steel slag as filter media in pollutants removal from domestic wastewater.

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2. Experimental

2.1 Set-up for VFARF and HFARF Performance Study on Nitrogen Removal

Primarily treated domestic wastewater was pumped using peristaltic pumps (Watson Marlow into the vertical flow ARF and horizontal flow ARF base using 15mm reinforced plastic pipework connected to a polyninyl chloride inlet strainer heads located at the base of both ARF systems. In addition, both ARF was installed with air flow meters and aerated by using JUN Air Compressor as described in Figure 1. The system was controlled by the required HLR and air flow rate that is 2.72 m^3/m^3.d and 10 L/min, respectively. Both filters were filled with the steel slag as filter media. The filters were run for 2.5 months. The influent and effluent of the VFARF and HFARF were collected twice a week for laboratory analysis on selected parameters including BOD, COD, TSS, TKN, AN, Alkalinity, Nitrate, Nitrite, pH, DO, Temperature and *E*-coli according to *Standard Methods for Water and Water Examinations* [6] at Wastewater Laboratory, UTHM.

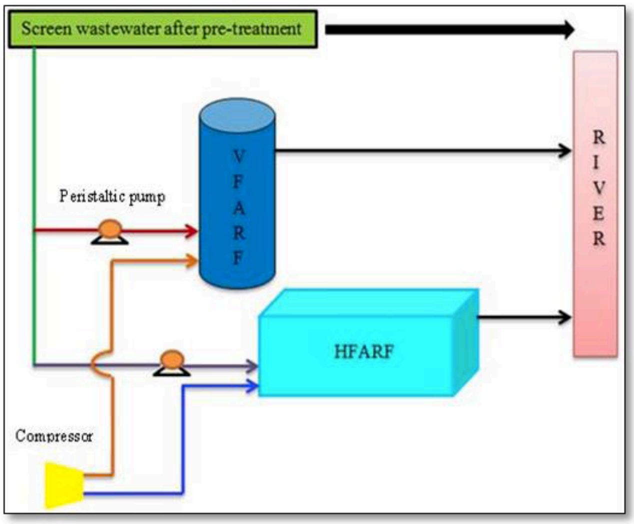

Figure 1. Layout of the experiment

3. Result and Discussion

3.1. The Performance of VFARF and HFARF System

The wastewater quality monitoring of VFARF and HFARF performance was took place in two months, from 13th November 2014 until 14th January 2015 at WWTP Taman Bukit Perdana, Batu Pahat, Johor. During the monitoring period, the wastewater influent and effluent were collected twice a week for laboratory analyses. This monitoring experiment was necessary to compare the performance between VFARF and HFARF in terms of removal of nitrogen. The removal efficiencies, influent and effluent concentration for monitoring parameters for both VFARF and HFARF are provided in Table 1. Based on the removal efficiency shown, the VFARF system has higher rate in removals compared to the HFARF, whish is more 80% in terms of BOD_5, TKN, AN, TSS, and *E-coli*. The discussion regarding the tabulated data is presented in the further subsections.

Table 1. Summary of monitoring data for the VFARF and HFARF system [a]

Parameter	Sampling Point			Removal Efficiency (%)	
	Influent conc.'s (Mean ± s.d.)	VFARF effluent conc.'s (Mean ± s.d.)	HFARF effluent conc.'s (Mean ± s.d.)	VFARF (Mean ± s.d.)	HFARF (Mean ± s.d.)
BOD_5	266.30 ± 269.71	24.69 ± 21.62	21.49 ± 16.39	86 ±10	88 ± 8
COD	426.06 ± 343.52	96.64 ± 49.05	70.78 ± 52.84	65 ±23	75 ±21
TKN	50.77 ± 22.47	5.43 ± 2.39	10.96 ± 5.57	89 ±7 [NE]	78 ±11 [NE]
AN	31.39 ± 8.96	0.84 ± 0.62	9.06 ± 4.27	97 ±2 [NE]	71 ±12 [NE]
Nitrate-N	0.00 ± 0.00	18.65 ± 6.10	6.42 ± 2.35	n.a	n.a
Nitrite-N	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	n.a	n.a
TSS	601.84 ± 591.16	30.53 ± 22.91	24.47 ± 17.86	86 ±17	88 ±15
Alkalinity	314.61 ± 206.98	107.08 ± 28.35	147.24 ± 16.20	n.a	n.a
E-Coli	50949.00 ± 29904.60	1405.15 ± 1564.11	2901.50 ± 3715.92	97 ±2	91 ±16
DO	0.19 ± 0.23	5.20 ± 0.84	3.75 ± 0.37	n.a	n.a
pH	6.28 ± 0.09	7.14 ± 0.27	6.99 ± 0.15	n.a	n.a
Temp, °C	31.2 ±0.7	31.1 ± 1.1	31.1 ± 1.1	n.a	n.a

[a] Note: All units are mg/L except pH and *E-coli* (cfu/ml), s.d.= Standard Deviation (n=19); n.a.= not available; [NE] = **nitrification efficiency**

3.2 Biochemical Oxygen Demand (BOD_5) Removal

The value of influent concentration in the WWTP is average at 266.30 ± 269.71 mg/L BOD_5. After two month of monitoring period, the BOD_5 effluent was slightly dropped with an average concentration of 24.69 ± 21.62 mg/L and 21.49 ± 16.39 mg/L for the VFARF and HFARF systems, respectively as presented in Figure 2. Meanwhile, the average removal efficiency for VFARF was 86% ± 10, whilst the average removal of HFARF was 88% ± 8 as shown in Figure3. Both VFARF and HFARF systems were efficiently removed BOD_5 from domestic wastewater and not statistically significant different in terms of removal efficiency and effluent quality as the *p*-value was 0.751 and 0.817 respectively. Both systems were performed well in terms of BOD_5 removal. In addition, both systems are able to produce effluent quality within the permissible limit of Standard B which is 50 mg/L under Environmental Quality (Sewage) Regulations 2009.

The reduction of BOD_5 concentration took place as soon as the wastewater in terms of biodegradable organic matters enter the VFARF and HFARF system due to highly aerated filter system with high concentration of dissolved oxygen as well as the porous media within the filters. Furthermore, aerobic degradation of dissolved organic matter is developed by the aerobic heterotrophic bacteria. Vymazal in [7] has stated that ammonifying bacteria also degrade organic compounds containing nitrogen under aerobic conditions. The microorganisms use oxygen as a source of energy for growth during the decomposition process of organic carbon to carbon dioxide.

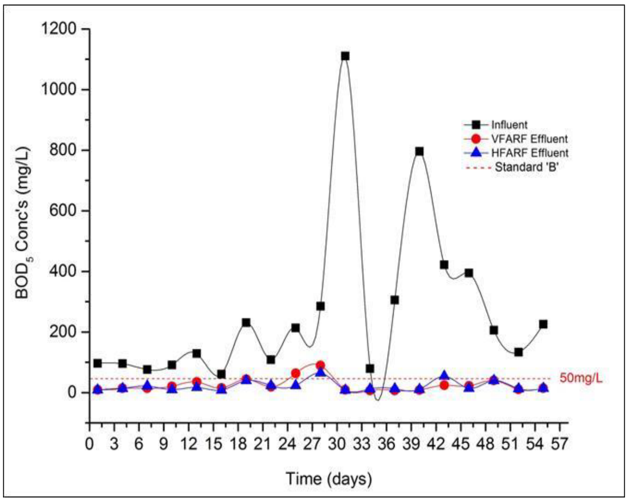

Figure 2. BOD_5 concentrations in the WWTP influent and effluent of VFARF and HFARF

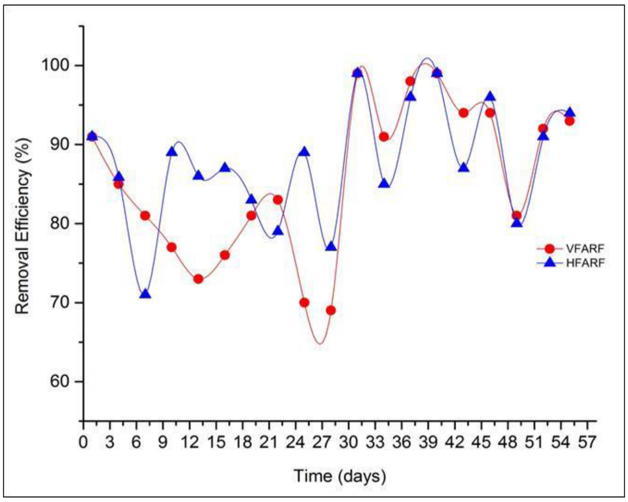

Figure 3. Removal efficiency of BOD_5

3.3 Chemical Oxygen Demand (COD) Removal

The COD concentration from wastewater influent is at an average 426.06 ± 343.52 mg/L then COD value was reduced to an average 96.64 ± 49.05 mg/L for VFARF and 70.78 ± 52.84 mg/L for HFARF as provided in Figure 4. In terms of filter performance, the HFARF showed a higher performance than the VFARF in COD removal.

The removal efficiencies were found to be at an average of 65% ± 23 in the VFARF and 75% ± 21 in the HFARF as illustrated in Figure 5. Based on the *t-test* analysis, both VFARF and HFARF systems were efficiently removed COD from domestic wastewater without showing any statistical significant different in terms of removal efficiency and effluent quality as the *p*-value was 0.167 and 0.127 respectively. Some of the COD value might be associated with the suspended solid that settle in the filter. Besides that, COD removal efficiency increased due to the oxygen content in the filter is higher. As for COD, both systems are able to produce effluent quality within the permissible limit of Standard B which is 200 mg/L.

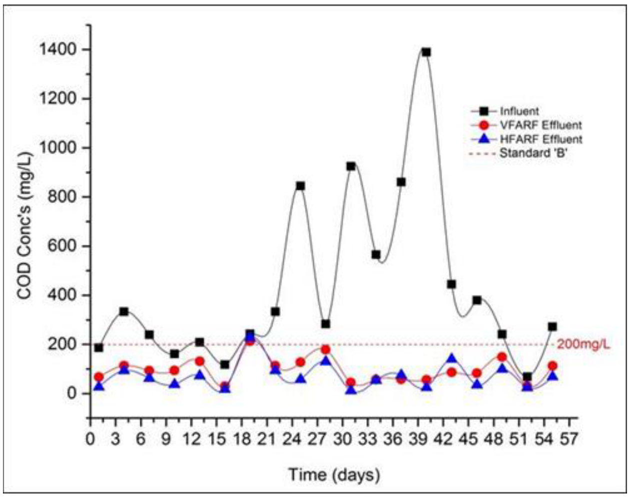

Figure 4. COD concentrations in the WWTP influent and effluent of VFARF and HFARF

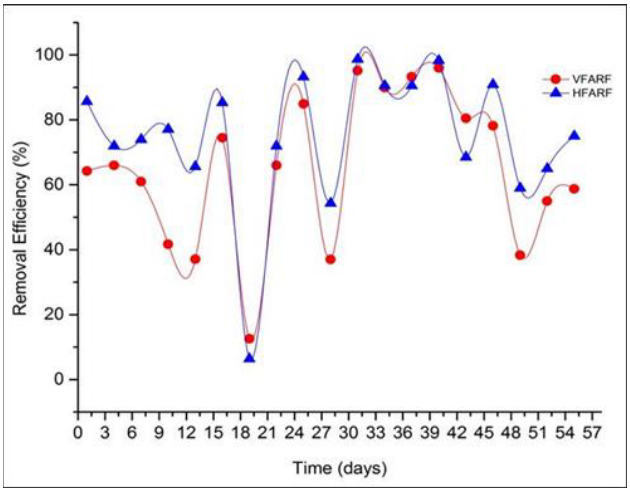

Figure 5. Removal efficiency of COD

3.4 Total Suspended Solids (TSS) Removal

The TSS influent concentration entering the VFARF and HFARF systems were produced an average of 601.84 ± 591.16 mg/L during the monitoring period and after treatment. The VFARF was able to produce an average of 30.53 ± 22.91 mg/L in the filter effluent, equal to a removal efficiency of 86% ± 17. On the other hand, the HFARF achieved 88% ± 15 of removal efficiency with an average effluent concentration of 24.47 ± 17.86 mg/L as provided in Figure 6 and 7. Based on the *t-test* analysis, the effluent and removal efficiency of TSS results were not statistically significant different as the *p*-value was 0.297 and 0.686 respectively for both VFARF and HFARF systems. From the results, it shows that both systems performed well in removing suspended solid. It is proved by the [8] that horizontal subsurface flow provide a higher filtration capability for solid matter removal. In terms of TSS, both systems are able to produce effluent quality within the permissible limit of Standard B which is 100 mg/L.

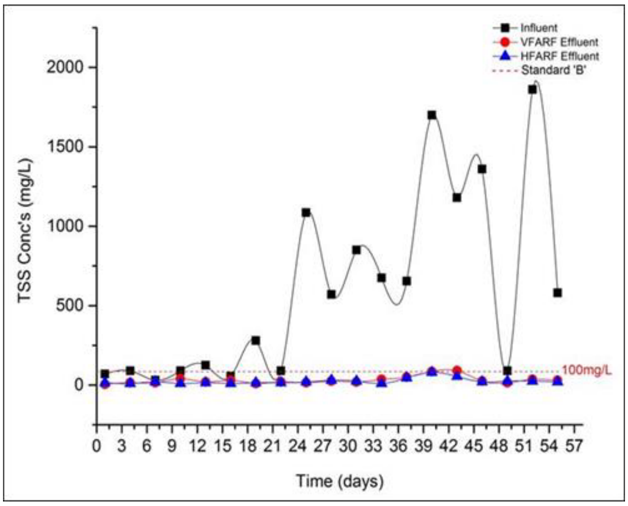

Figure 6. TSS concentrations in the WWTP influent and effluent of VFARF and HFARF

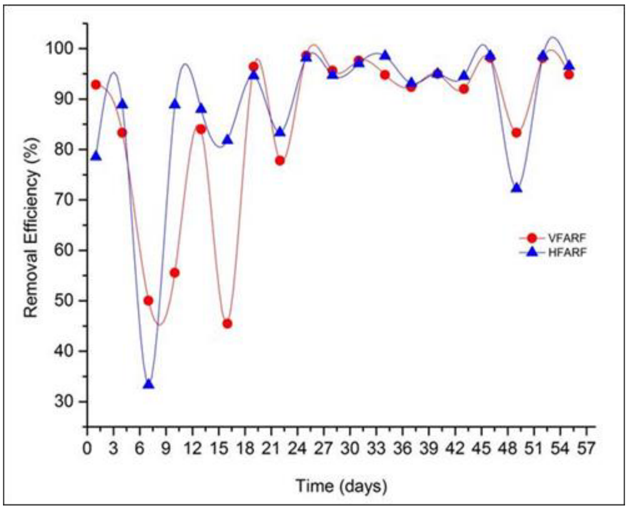

Figure 7. Removal efficiency of TSS

3.5 Total Kjeldahl Nitrogen (TKN) Removal

Total Kjeldahl Nitrogen (TKN) represents the sum of organic nitrogen, ammonia nitrogen (NH_3) and ammonium nitrogen (NH_4^+). However, most of the ammonia in wastewater is found in the form of ammonium ion. TKN concentration in the influent was at an average 50.77 ± 22.47 mg/L then was removed after treatment in VFARF and HFARF as their removal efficiencies achieved the averages of 89% ± 7 and 78% ± 11, respectively as shown in Figure 8. Thus, the average final effluent for VFARF was 5.43 ± 2.39 mg/L and 10.96 ± 5.57 mg/L for HFARF as provided in Figure 9. In terms of TKN removal and effluent quality, VFARF performed better than HFARF and it is also statistically significant different as the *p*-value was 0.000 and 0.002 respectively. From the result obtained, VFARF was successfully reduced the nitrogen from domestic wastewater.

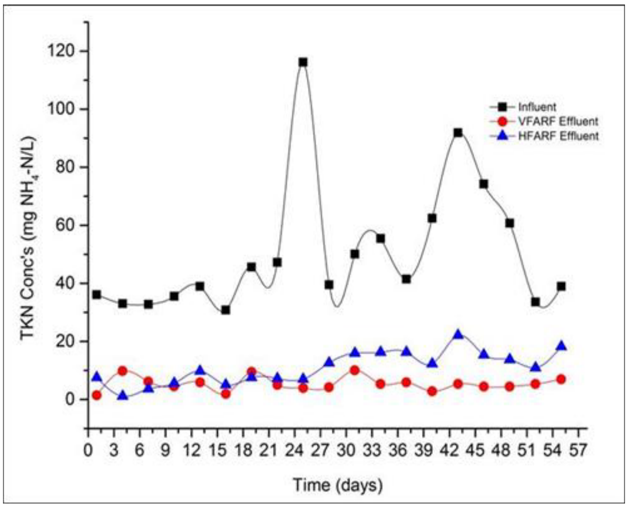

Figure 8. TKN concentrations in the WWTP influent and effluent of VFARF and HFARF

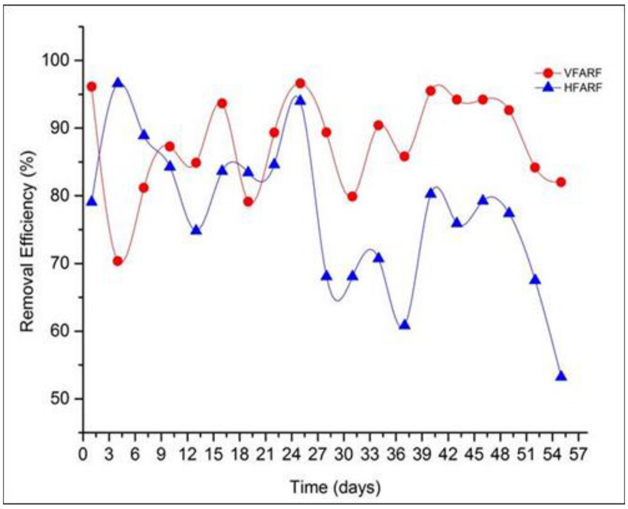

Figure 9. Removal efficiency of TKN

3.6 Ammonium Nitrogen (AN) Removal

Ammonium nitrogen (AN) from wastewater had an average of 31.39 ± 8.96 mg/L of influent concentration. AN was effectively removed in the VFARF compared to the HFARF. The removal efficiency in the VFARF system averaged 97% ± 2, which produced an average of 0.84 ± 0.62 mg/L in the final effluent. However, the removal efficiency was found to be slightly lower in the HFARF system as achieved an average of 71% ± 12 AN removal with the final effluent concentration average of 9.06 ± 4.27 mg/L as provided in Figure 10 and Figure 11. From the results it shows that the removal of ammonium nitrogen was excellent in VFARF system compared to HFARF system and it is statistically significant different as the *p*-value was 0.000 for both VFARF and HFARF systems. Both systems were consistently produced good effluent quality and comply with the effluent permissible limit for 'standard B' which is 20 mg/L. From this observation, it shows that nitrification process was took place in this treatment system as AN has been well removed under aerobic condition filter system.

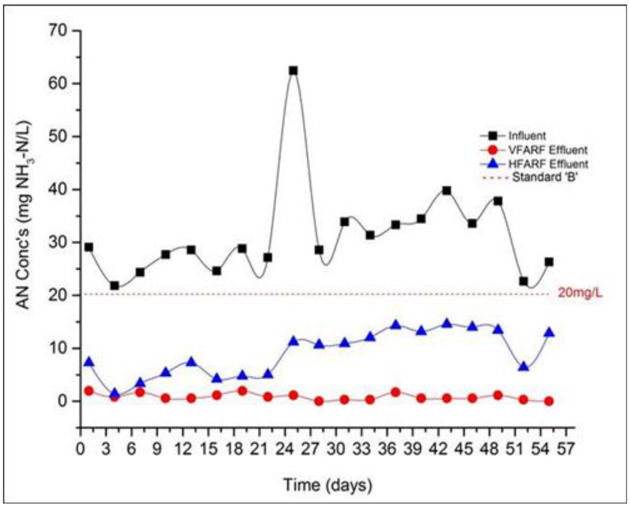

Figure 10. AN concentrations in the WWTP influent and effluent of VFARF and HFARF

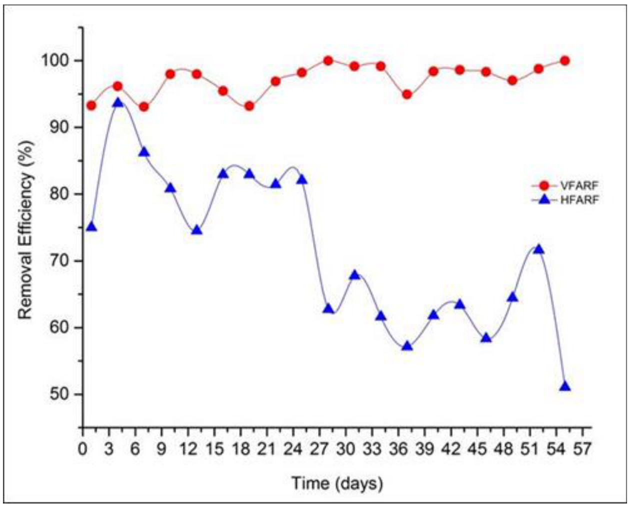

Figure 11. Removal efficiency of AN

Furthermore, dissolved oxygen was found to be higher in the VFARF system with an average 5.20 ± 0.84 mg/L, whilst an average of 3.75 ± 0.37 mg/L was determined in the HFARF system as illustrated in Figure 12. Pertaining to the increasing level of DO in the system, the VFARF system provides more favorable conditions for nitrification to occur as well as further removal of biodegradable organic matters. Therefore, in a highly oxygenated system such as in the 1.5m depth of VFARF, more ammonium ions (NH_4^+) were oxidized to nitrate-nitrogen (NO_3-N) as compared to the 0.5m depth of HFARF due to DO level within the system.

In this experiment, high concentration of nitrate-nitrogen (NO_3-N) found in the VFARF effluent shows that nitrification process has taking place as AN has been converted to nitrate with the present of nitrfiers; *Nitrosomonas* and *Nitrobacter.* An average concentration of NO_3-N in the VFARF effluent was 18.65 ± 6.10 mg/L whilst in the HFARF the average was 6.42 ± 2.35 mg/L as shown in Figure 13. Effluent quality from both systems within permissible limit of 'Standadr B' which is 50 mg/L. From this observation, conversion of NO_3-N was slightly higher in the VFARF compared to the HFARF. This condition shows that nitrification rate was slightly higher in the system with higher NO_3-N concentration in final effluent. Therefore, this observation then supported by nitrification data that was relatively higher in the VFARF system compared to the HFARF system as illustrated in Figure 14. The average of nitrification efficiency in the VFARF and HFARF were 97% ± 2 and 71% ± 12 respectively. The rate of nitrification was found to be higher in VFARF system and it is statistically significant different as the *p*-value was 0.000 for VFARF and HFARF Therefore, the VFARF is more effective than the HFARF. Furthermore, according to [9], vertical flow rock filters mostly perform better than horizontal flow systems as ones located in Veneta, Oregon and West Monroe, Louisiana. Theoretically, the rates of nitrification are higher when the DO levels in the system are higher.

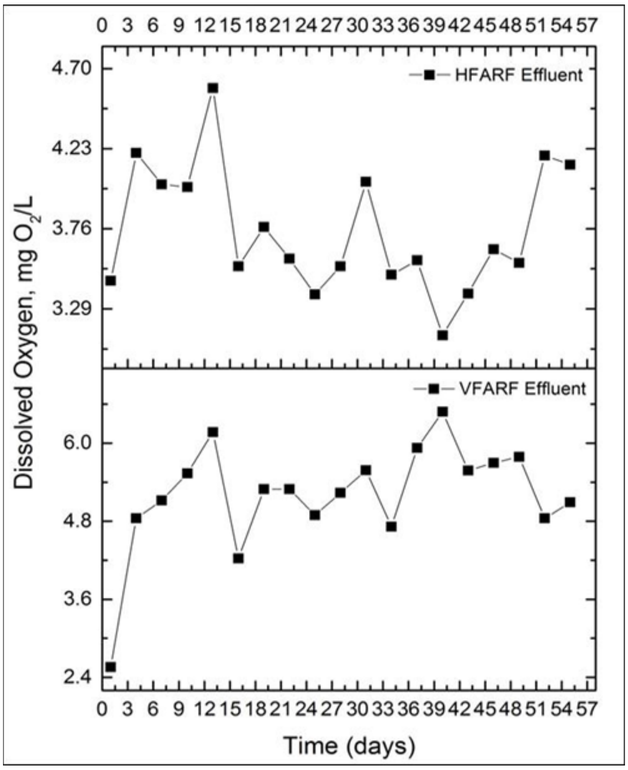

Figure 12. DO profiles of VFARF and HFARF effluent

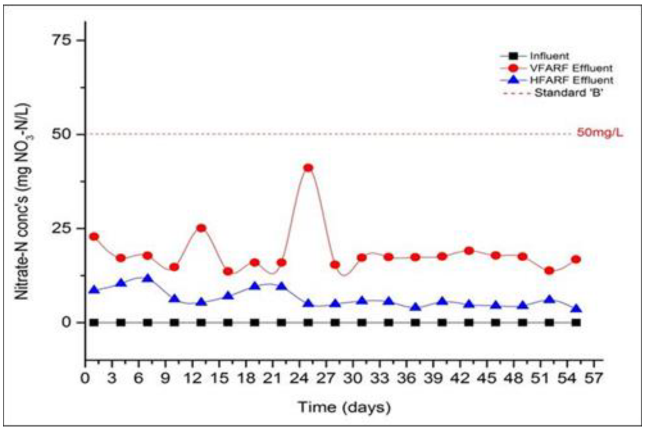

Figure 13. Nitrate-nitrogen concentrations in the WWTP influent and effluent of VFARF and HFARF

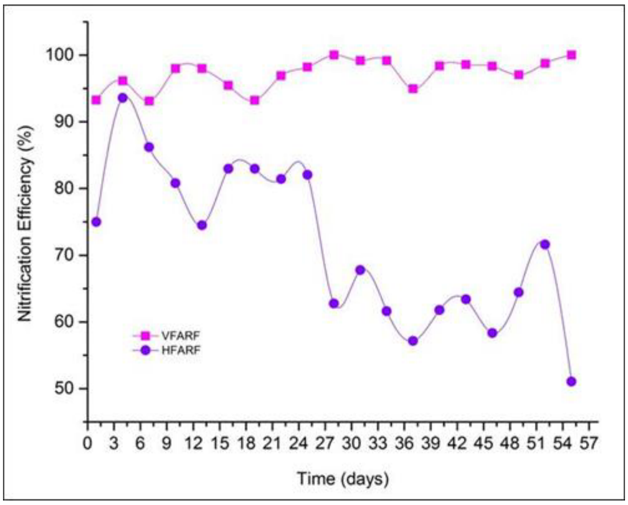

Figure 14. Nitrification efficiency of VFARF and HFARF systems

The average daily temperatures data were collected throughout this experimental period. The data was obtained from *thermo button* located at experimental station at WWTP Taman Bukit Perdana, Batu Pahat. The temperature profiles of VFARF and HFARF was given in Figure 15 which found to be within the range 28.0 – 32.8ºC. Range of temperature during this experiment was undertaken fall within the optimum range of nitrification to take place as reported by Gerardi [10]. Therefore, it is expected that favourable environment also increased the nitrification rate during this study.

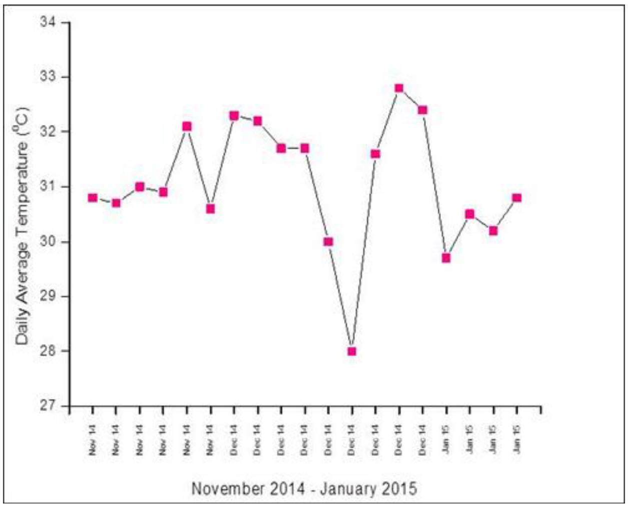

Figure 15. Temperature profile of WWTP influent and effluent of VFARF and HFARF

3.7 pH and Alkalinity

The pH value for influent concentration is in acidic pH, i.e. 6.11-6.46 during the monitoring period. After treatment, the pH for VFARF and HFARF were in the neutral pH with an average of 7.14 ± 0.27 and 6.99 ± 0.15, respectively. This condition occurred most probably due to consumption of alkalinity since the nitrification of nitrogen within the treatment process. Figure 16 shows the pH profile in the influent and VFARF and HFARF during monitoring period.

The high alkalinity in the influent is in the range 180 to 900 of total alkalinity mg/L as $CaCO_3$ as can be seen in the Figure 17. Moreover, the total alkalinity was found to be further consumed rather than generated in VFARF and HFARF effluent. The alkalinity in the effluent from VFARF was lower than in the HFARF which is range from 77 to 175 mg/L as $CaCO_3$ and 115 to 170 mg/L as $CaCO_3$, respectively. This condition might be due to the nitrification rate which was significantly higher in the VFARF compared to the HFARF as both VFARF and HFARF systems were statistically significant different in terms of as the *p*-value was 0.000.

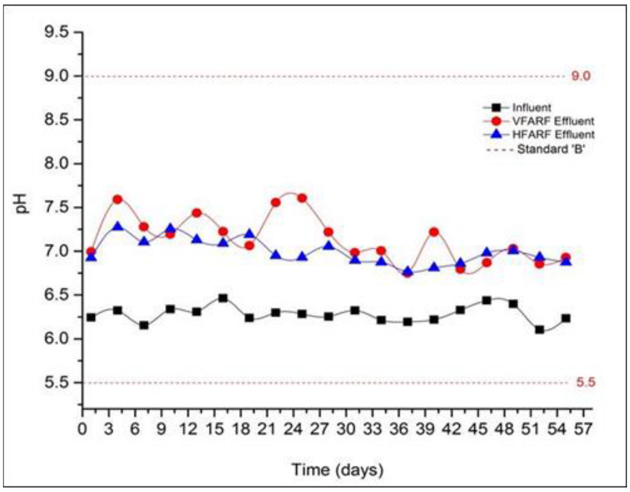

Figure 16. pH profile of WWTP influent and effluent of VFARF and HFARF

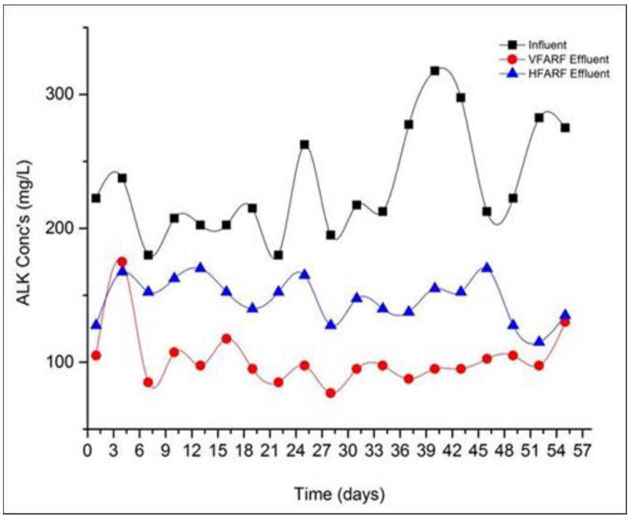

Figure 17. Alkalinity concentrations of WWTP influent and effluent of VFARF and HFARF

3.7 Escherichia coli (*E-coli*)

E-coli is naturally present in the intestinal tracts of warm-blooded animals and is a member of the fecal coliform group of bacteria and also used as an indicator of fecal contamination of waterways [11]. The *E-coli* count from wastewater had an average of 50.949 x 10^3 cfu/ml ±

29.9046 x 10^3 cfu/ml of influent concentration. *E-coli* were efficiently removed in the VFARF compared to the HFARF. The removal efficiency in the VFARF system is 97% ± 2, which produced an average of 1.40515 x 10^3 cfu/ml ± 1.5641110^3 cfu/ml in the final effluent, meanwhile the removal efficiency in HFARF is 91% ± 16 with the final effluent concentration average is 2.9015 x 10^3 cfu/ml ± 3.71592 x 10^3 cfu/ml as showed in Figures 18 and 19. Both VFARF and HFARF systems were efficiently removed *E-coli* from domestic wastewater and not statistically significant different in terms of effluent quality and removal efficiencies as the *p*-value was 0.315 and 0.165 respectively.

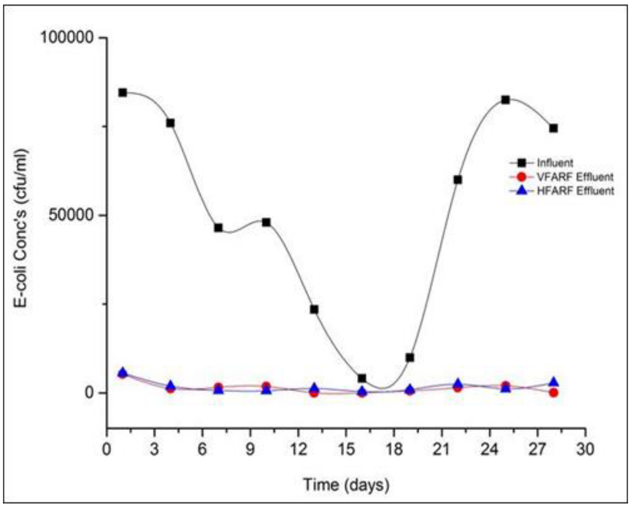

Figure 18. *E-coli* concentrations in the WWTP influent and effluent of VFARF and HFARF

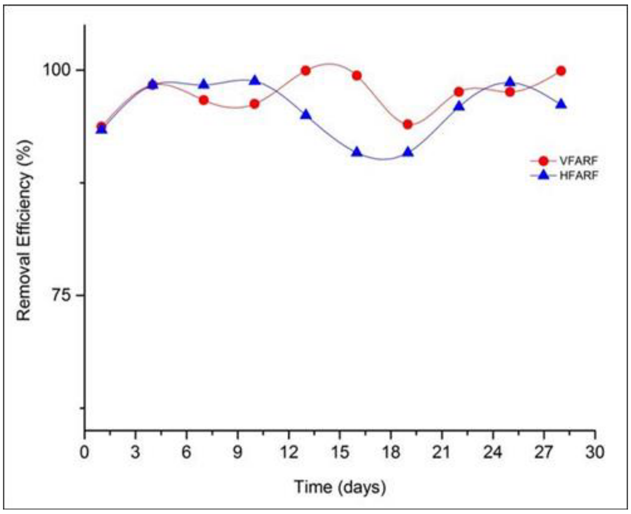

Figure 19. Removal efficiency of *E-coli*

4. Conclusion

Based on the experimental results reported herein, the objectives as presented in Chapter 1 (Section 1.3) have been achieved. A number of conclusions can be drawn from the present study are:

1. The VFARF system has emerged as one of the more competitive and economic treatment systems, particularly for nitrogen removal serving low-income and small communities' wastewater in comparison to the HFARF. Moreover, the VFARF system had a lower land area requirement than the HFARF.
2. The most effective degradation zone for BOD_5, TSS, TKN, and ammonium-nitrogen is VFARF system.
3. Both systems are able to produce very good effluent quality as all the selected parameters were within the permissible limit of Standard B Malaysian Environmental Quality (sewage) Regulation 2009.

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