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Performance of an Upflow Sand Filter as a Point-of-Use Treatment System in Rural Areas

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An upflow sand filter operated in incremental filtration rates (0.072, 0.181, 0.481 $m^3 m^{-2} h^{-1}$) was studied for turbidity, total suspended solids (TSS), ammonia (NH_4), and total coliform removal rates. Each cycle lasted for 45 days. The filter bed was made of sand with 0.10 mm D_{10} and supported by 0.49 mm and 2.10 mm gravel with a total bed depth of 0.50 m. Turbidity removal was recorded above 80% in all cycles with a maximum concentration of 7.29 NTU. TSS removal was maintained at over 90%, with an average discharge of 4.77 mg/L in all cycles. The NH_4 removal increased steadily to 91% for 0.072 $m^3 m^{-2} h^{-1}$ and 93% for 0.181 $m^3 m^{-2} h^{-1}$ filtration rate. The algal bloom occurrence at 0.481 $m^3 m^{-2} h^{-1}$ filtration rate overloaded the system with NH_4, declining the removal rate to 45%. Total coliform removal recorded an average of 99% in 0.072 $m^3 m^{-2} h^{-1}$, 89% in 0.181 $m^3 m^{-2} h^{-1}$, and 66% in 0.481 $m^3 m^{-2} h^{-1}$. A high filtration rate resulted in a shorter contact time between pollutants and microorganisms within the filter bed, which reduces the removal efficiency. The Shearing effect was also experienced where the attachments of particles and bacteria were minimised.

Keywords: Rural water supply; upflow sand filter; point-of-use water treatment; surface water treatment

I. INTRODUCTION

Many rural communities in developing countries are still without access to a treated water supply. Often, these populations turn to alternatives such as rainwater, groundwater and surface water which are commonly untreated. These waters are polluted by suspended solids, turbidity, bacteria and sometimes ammonia (Sarbatly *et al.,* 2020). Ingestions of untreated water will leave the consumer susceptible to waterborne diseases such as dysentery, typhoid, polio, cholera, and diarrhoea (World Health Organisation and WEDC, 2013). Point-of-use water treatment installed in every rural household can ensure that the water consumed is of acceptable quality. Such treatment should be straightforward, utilise locally available resources and, most importantly, remove all necessary pollutants.

Sand filter is one of the most effective and simplistic water treatment methods. It has been utilised for hundreds of years. Its effectiveness in removing major pollutants has been shown by the multitude and extensiveness of its usage alone. Nevertheless, the treatment using a downflow sand filter mainly depends on straining by the top layer on the sand bed called schmutzdecke, which often causes filter clogging and results in frequent backwashing (Grace *et al.,* 2016). Backwashing a downflow sand filter will cause significant filter downtime and reduce water quality.

Upflow sand filter has been applied in numerous water treatment processes to remove phosphorus, nitrogen, heavy metals, bacteria, algae, turbidity and suspended solids (Heikal *et al.,* 2017). Due to the upflow configuration, clogging is less susceptible, and backwash can be done more rapidly, reducing filter downtime (Smith, 1979). In an upflow sand filter, water enters at the bottom of the filter and will go through the gravel layers beneath the filter bed first. While acting as support, the gravel can aid as a pre-filtration stage, which performs similarly to a roughing filter. Pressured operation enables easy flowrate manipulation based on water demand.

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This research aimed to study the efficiency of a self-fabricated upflow sand filter as a point-of-use treatment to provide potable water in a rural setting. The upflow sand filter was fabricated using only locally sourced material that should be readily available for rural communities in an isolated locations. The upflow sand filter used in this research is easy to assemble and operate by any unskilled or semiskilled personnel. The upflow sand filter is expected to cater to the water demand for small households in rural areas.

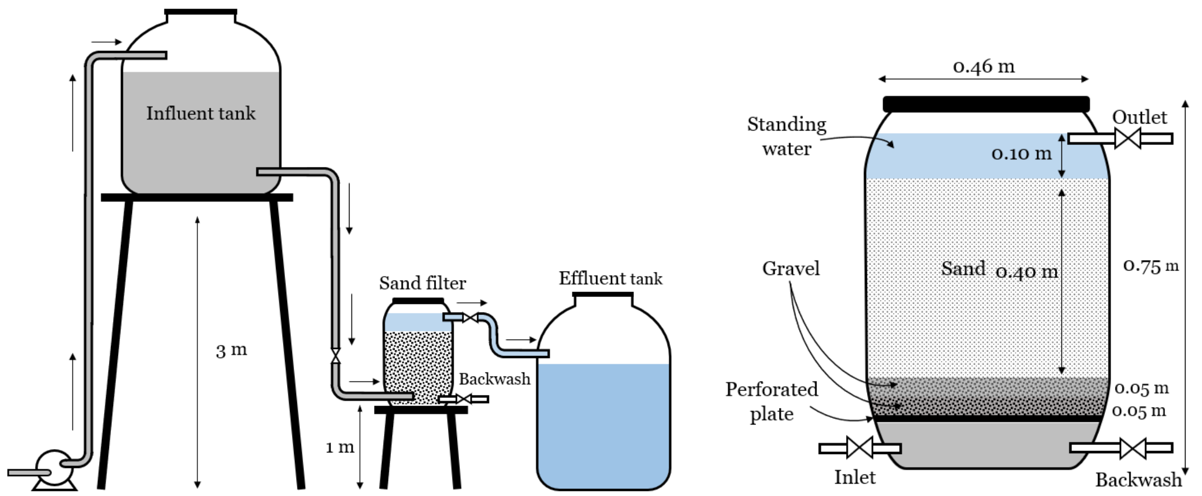
II. MATERIALS AND METHODS

A. Surface Water

The experiment was conducted within the compound of the Engineering Faculty, Universiti Malaysia Sabah. As there was no surface water supply available within the compound, piped water was augmented using a mixture of sand and ammonium sulphate $(NH_4)_2SO_4$. This combination has created feed water high in turbidity, TSS, Total Coliform, and NH_4, mimicking the water quality of a local river in Sabah (Cleophas *et al.,* 2013). The mixture was allowed to settle and pumped into the influent tank. A ratio of 0.5 kg of sand in every 100 L of water was calculated. This process created contaminated water with high turbidity, suspended solids and Total Coliform content. $(NH_4)^2SO_4$ was added to increase the concentration of ammonia, NH_4. 1 g $(NH_4)^2SO_4$ was calculated for each 100 L of water to create 3 mg/L of NH_4 concentration.

B. Upflow Sand Filter

A sand filter unit was fabricated from high-density polypropylene (HDPE) drum sizing 0.74 m in height and 0.46 m in average diameter. A perforated stainless-steel plate with 12 mm thickness was used as support, installed 0.10 m from the sand filter bottom floor, allowing a 0.10 m buffer zone for sedimentation to occur for heavier solids. Inlet and outlet pipes were installed on a 40 mm diameter HDPE pipe to accommodate the high flowrate for sand filter backwashing. The sand filter inlet pipe was connected to a 1500 L water tank elevated approximately 3 m to create water pressure. The schematic of the treatment system and design of the sand filter is as depicted in Figure 1.



(a) **(b)**

Figure 1. (a) Upflow sand filter system schematic, and (b) sand filter bed design

C. Sand Filter Bed

To ensure the experiment is conducted using local material, sand media were obtained from local rivers in Tamparuli, Sabah, Malaysia. Samples were washed and prepared based on the method described in (CAWST, 2009). The sand size ranged from <0.075 to 2 mm, with 0.10 mm D_{10} and 2.6 uniformity coefficient. Two layers of gravel support were used, each with 0.05 m thickness. Each gravel support measured effective size was 0.49 mm and 2.10 mm, respectively. The support layer was laid in a collective of small layers to ensure even distribution and compaction were achieved to promote even water flow distribution during filter operation. After the support was assured to be even, the sand media were poured in small quantities before levelling and distributed across the filter surface. This process was repeated until the sand bed height reached 0.40 m height. Before commissioning, the filter bed was allowed to be fluidised for 30 minutes and left to resettle.

D. Operational Parameters and Water Analysis

To study the efficiency of contaminants removal, three different filtration rates were used, i.e.: (Q1) 0.072 $m^3 m^{-2} h^{-1}$, (Q2) 0.1805 $m^3 m^{-2} h^{-1}$ and (Q3) 0.4813 $m^3 m^{-2} h^{-1}$, The filtration rates correspond to three production capacities 96, 240, 640 L per day that can cater for a small household. Each cycle was conducted consecutively for 45 days and operated based on eight operating hours daily. The establishment of microorganisms within the filter bed was allowed for eight weeks before the experiment was conducted. Turbidity, TSS, NH_4, and total coliform count were monitored every 3 to 4 days intervals. The turbidity was tested using HACH 2100AN Turbidimeter at 860 nm LED wavelength. TSS was tested using the ASTM D5907-10 method. NH_4 was determined using HACH method 10023, Salicylate Method. The total coliform count was determined using the membrane filtration method and incubated in Membrane Lauryl Sulphate Broth at 37 ± 0.5 ℃ for 12 hours.

III. RESULTS AND DISCUSSION

A. Turbidity and TSS Removal

Particulate removal reflected by turbidity and TSS removal is depicted in Figures 2 and 3. Throughout the Q1 experiment, increasing removal was seen with a maximum of 96.1% for turbidity and 100% for TSS after 5 days of operation. The maximum concentration of turbidity and TSS recorded throughout the operation was 6.55 NTU and 9 mg/L, respectively. A lower removal rate during the initial stage of operation suggests the requirement for the sand particles to settle and compact after being fluidised during the commissioning stage. Microorganism layers were still undergoing the maturation stage within the sand bed, which will further assist particle straining. During active filtration, the accumulation of particles on the sand surface further decreases the pore size between sand particles and increases the straining effect.

Consecutive operation under a slightly higher filtration rate of Q2 does not affect the ability to remove suspended particles. Good removal percentage was recorded right after the operation, at 97.2 % for turbidity and 94.4 % for TSS. The removal percentage was maintained at 83.5 – 97.62 % for turbidity and 91.2 to 100 % for TSS. The maximum treated water reading obtained for turbidity and TSS were 1.97 NTU and 2 mg/L, respectively, whereby the maximum influent fed into the sand filter was 36.5 NTU and 46 mg/L. At this stage of operation, the ecosystem within the sand filter has already matured, and particle attachment within the filter bed has fully developed. Furthermore, the filtration rate was not high enough to cause shear stress to drag any particle out of the sand filter bed.

The change of velocity to Q3 has been shown to reduce the removal of turbidity and TSS slightly. At the beginning of the filtration rate change, the turbidity removal was recorded as above 90%. However, it quickly declined over the next seven days to 80%. This was caused by an increased filtration rate that may elevate the pressure within the sand filter bed and cause a breakthrough of particles. An algal bloom was experienced during the operation within the untreated water tank on the 12th day due to static water conditions due to a faulty pump. This was reflected in the result where turbidity reading in the treated water was recorded at 2.08 NTU and 6 mg/L for turbidity and TSS, respectively. However, the removal rate of both parameters was still above 80%. The algae bloom continued for several days until algae growth spread within the sand filter bed, affecting the treated water quality. On the 19th day of operation, the removal efficiency had sharply declined to 32.3 % for turbidity and 32.1 % for TSS. Traces of algae were seen in the treated water (7.92 NTU of turbidity and 32 mg/L of TSS reading), making filter backwash necessary. Turbidity and TSS removal percentages were readjusted to above 90% after the backwash and maintained throughout its operation.

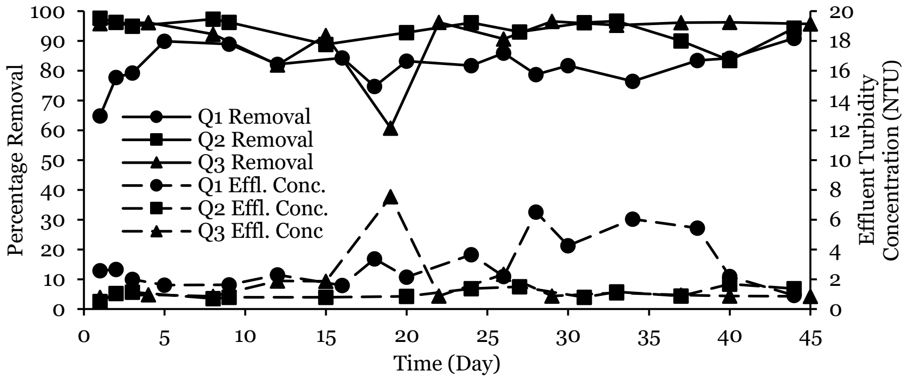


Figure 2. Turbidity removal performance (%) and effluent concentration (NTU)

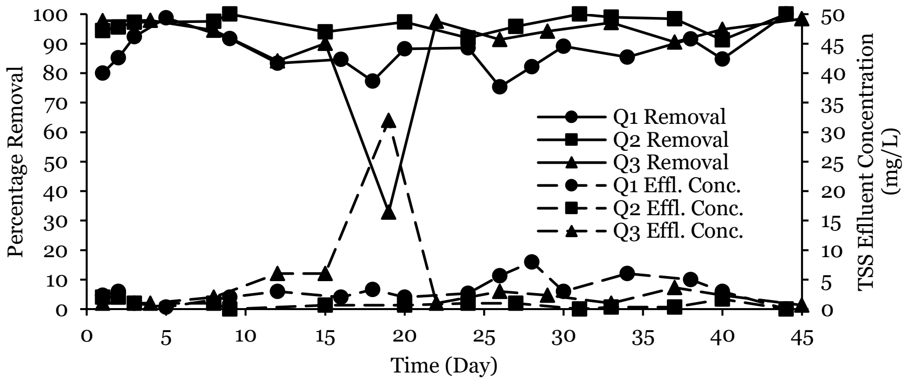


Figure 3. TSS removal performance (%) and effluent concentration (mg/L)

The gravel layer, which acts similarly to a roughing filter also contributed to the removal of turbidity and TSS. Through time, a layer of microorganism film is established on the gravel surface. Fine particles attach to these layers, aiding the removal efficiency of the roughing filter. Furthermore, the removal of particulate matter within the filter bed bottom was aided by a 10 cm buffer area beneath the roughing filter. Sedimentation of bigger particulate matter occurs within the buffer zone, reducing the load of pollutants and increasing the efficiency of the upflow sand filter. Both the buffer zone and roughing filter are vital elements to reduce the pollutant load into the sand bed and ensure the longevity of the upflow sand filter lifespan. However, it is essential to note that to ensure sedimentation occurs effectively within the buffer zone and roughing filter, the flow within these two units remains as laminar flow. Further increase in filtration rate will hinder the sedimentation process due to turbulence. An increase in filtration rate also causes pressure that will push the particulate matter further into the filter bed.

B. Nitrogen Removal

Upon commissioning, the acclimatisation period was necessary for oxidising bacteria to develop and mature before achieving optimum removal. This was seen in the first 15 days of the Q1 operation (Figure 4). Subsequently, the system maintained its performance above 80% removal with slight fluctuation until the end of its 45 days of operation. An increase in filtration rate during the Q2 operation shows a more stabilised removal with the occasional drop of removal caused by the sudden increase in loading rate in the system (seen on days 8^{th} and 27^{th}). However, throughout the operation, similar to the previous filtration rate, the removal was above 80%. During the Q3 operation, an increase of NH4 content was experienced in the untreated water due to a faulty pump, causing the water to be static for a longer time. It was reflected by the algae bloom in the untreated water that has spread within the sand filter bed. Although algae are known to remove nitrogen content, the contact time during the experiment is insufficient to aid in high removal. Backwash was necessary to remove the algae within the filter bed. After the backwashing process, several days were required for the oxidising bacteria to re-establish and stabilise. Removal of NH_4 remained above 70% throughout the operation, lower than in the previous operational filtration rate. Table 1 summarises the loading and removal rates recorded throughout the operation under three different filtration rates.

Better nitrogen removal is associated with a low infiltration rate (de Rozari *et al.,* 2018) due to the contact required by the oxidising bacteria to utilise the available NH4. In this research, the upflow sand filter could cater to nitrogen removal even at a slightly higher filtration rate at Q2 (0.181 m3m-2h-1). The performance declined with a further increase in the filtration rate. Nevertheless, NH4 removal may be limited by several other factors. Lack of oxygen concentration deeper within the bed could inhibit nitrifying bacteria growth. Lower oxygen concentration is mainly caused by it being fully utilised by other microorganisms beneath the sand layer as the sand filter operates in an upflow configuration. Nevertheless, as nitrate and nitrite were not tested during the experiment, in-depth insight into the treatment efficiency for potable water still needs to be improved.

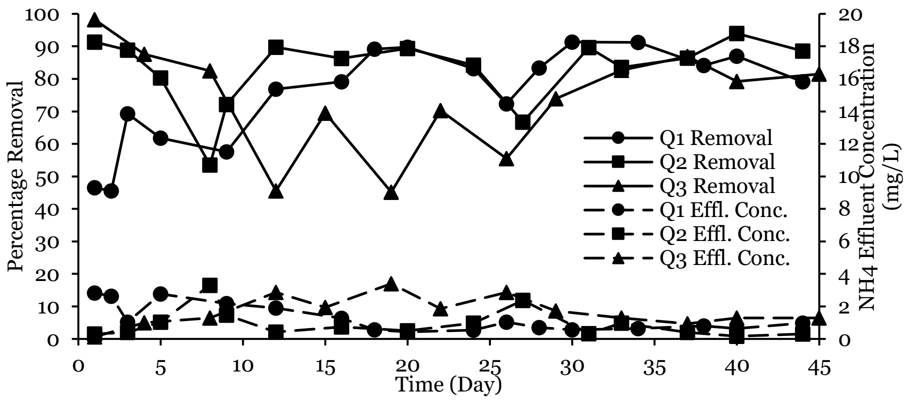


Figure 4. NH_4 removal performance (%) and effluent concentration (mg/L)

Table 1. Loading and removal rate of NH_4 (mg/L per hour) ± standard deviation with removal percentage of NH_4

Value	Q1	S.Dev	Q2	S.Dev	Q3	S.Dev
Loading Rate (mg/L per hour)						
Max	1.184		2.563		7.73	
Min	0.457	0.008	0.951	0.058	5.07	0.17
Average	0.755		1.675		6.51	
Removal Rate (mg/L per hour)						
Max	0.948		1.865		7	
Min	0.318	0.009	0.842	0.069	2.31	0.2
Average	0.573		1.346		4.88	
Removal percentage (%)						
Max	91.32		93.98		98.71	
Min	45.51	0.80	53.52	1.99	45.16	1.88
Average	75.71		82.97		73.71	

C. Total Coliform Removal

The total coliform removal trend shows a decline in total coliform removal with the increase in filtration rate. During the Q1 operation, a maximum of 100% removal was achieved and declined to 99.86% and 86.71% for Q2 and Q3, respectively (Figure 5).

The upflow sand filter was seen to remove coliform concentration right after activation of the filter, indicating straining and attachment of microbial process. This performance has been maintained throughout the 45 days of Q1 operation. Reduction of removal rate at increased filtration rate results from the shorter contact time between removable bacteria content to microorganisms within the sand filter bed. During the Q2 operation, total coliform removal gradually improved and stabilised above 90% after 30 days. This shows that after disturbance of particle equilibrium within the bed due to filtration rate adjustment, the system requires a buffer time for acclimatisation to reach its optimum performance in terms of bacterial removal due to the sensitivity of biological treatment. The complication during the Q3 operation is reflected in the reclining bacteria removal performance. Although steady improvement was seen after backwash, the overall escalation of shear stress across the filter bed has resulted in a lower removal of bacteria as chances of bacterial contact with microorganisms lowered. The attachment of particles and bacteria was also inhibited due to the shearing effect.

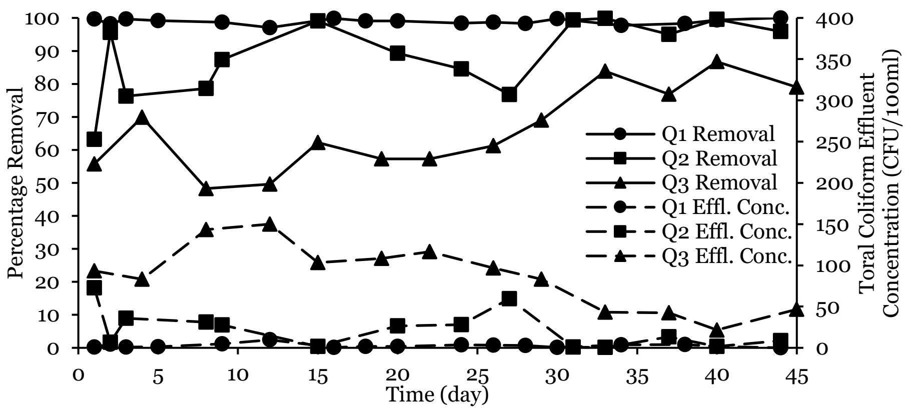


Figure 5. Total Coliform removal performance (%) and effluent concentration (CFU/100ml)

To understand the removal action of total coliform within the upflow sand filtration, a comparison between the conventional downflow slow sand filter and rapid sand filter is necessary. In a slow sand filter with a downflow configuration, the removal action depends on a collection of physical, physicochemical, and biological processes. Removal of coliform is more aligned with the development of microorganism populations (Calvo-Bado *et al.,* 2003). On the other hand, in a rapid sand filter where water pressure drives the filtration, retention of coliform is more inclined towards physical removal of transport and attachment, although also affected by physicochemical and biological removal. In research conducted by (Yu *et al.,* 2015), coliform retention was seen to increase gradually when the filtration rate increased from 5 – 9 m/h. However, further filtration rate increase shows the opposite effect where coliform retention has declined at 11 – 15 m/h. A higher filtration rate will cause lesser retention of coliform due to shorter contact time and shearing stress. The current research shows similarities to the rapid sand filtration behaviour as it operated based on pressured flow. This also manifests in the results, as higher filtration rates have resulted in lower coliform removal. With further increases in filtration rate, pre-treatment chemical additives such as coagulant will be necessary to maintain the removal rate.

On the other hand, acclimatisation is a crucial aspect to consider whenever a biological element is involved. In this study, the filtration process was consecutively operated for all filtration rates without refreshment of the sand media, making the media more acclimatised with each cycle. Statistical analysis through one-way ANOVA shows a significant difference for Turbidity, TSS, and Total Coliform removal, showing that the more acclimatisation period may have aided the removal efficiency in Q2 and Q3.

Table 2. One-way ANOVA analysis

	Turbidity	**TSS**	**Total coliform**	**NH_4**
P-value	0.002	0.013	0.007	0.19

Note: alpha value of 0.05

IV. CONCLUSION

The efficiency of the upflow sand filter in removing pollutants was investigated with filtration rate variation across the filter bed. The result shows that an increase in filtration rate had little to no significant effect on the removal of turbidity and TSS. However, it has significantly impacted the removal of NH_4 and total coliform. Other main findings from the research are:

- The buffer zone and gravel layer beneath the sand bed are essential in removing pollutants. Flowrate within the buffer zone should remain as laminar flow to maintain good removal rates.
- An increase in filtration rate increases shear stress, reducing the chance of microorganism and pollutant contact time and the chance of attachment onto the sand surfaces.
- At the beginning of the upflow sand filter activation, a buffer time is necessary to settle sand grains and establish layers of microorganism biofilm on the sand surface before the removal of pollutant stabilises.
- Removal of NH_4 was limited by a lack of dissolved oxygen and other nutrients within the deep bed. Further research on the quantification of anaerobic oxidising bacteria or nitrifying bacteria growth in relation to the depth of upflow sand filter will give a further understanding of the removal mechanism and capacity of the upflow sand filter.

This research found that the upflow sand filter can produce water with acceptable quality in a continuous operation of 8 hours daily. For an average usage of 100 L per capita per day, the upflow sand filter will cater to a small household of 6 people.

V. ACKNOWLEDGEMENT

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