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Performance of Sand Filtration System with Different Sand Bed Depth for Polishing Wastewater Treatment

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Abstract

Sand filtration is a polishing type of treatment system that is widely used as an efficient, cost-effective and simple treatment method. The efficiency of sand filtration relies mainly on the capacity of sand bed depth. Different sand bed depth affects the filtration rate and the contaminant removal differently. Hence, this study aims to investigate the effect of different sand media depth on the removal efficiency of the filtration process. An experimental sand filter with three design modifications of different sand bed depth, 30 cm, 60 cm, and 90 cm, was operated as polishing stage of an effluent from conventional activated sludge process. The highest filtration rate was recorded using sand depth of 30 cm. Higher filter bed depth result in lower filter rate which result in smaller filtrate volume. Highest E. Coli and COD removal, are 95.5% and 52.2%, respectively, recorded using 30 cm sand depth. Meanwhile, highest TSS and turbidity removal are 91.0% and 77.3%, respectively, with sand depth of 90 cm. Highest total coliform and BOD removal are 88.3% and 68.0% respectively by using sand depth of 60 cm. This study demonstrated that the sand filter is more efficient in removing suspended contaminants and coliforms compared to removing dissolved contaminants.

Keywords: Sand filtration; Sand bed depth; Polishing; Wastewater treatment; Coliform removal

1 Introduction

Over 2 billion people live in countries with high water stress. It was reported that about 4 billion of people suffer from severe water scarcity at least once a year [1]. According to Food and Agricultural Organization (FAO), the global water withdrawal increases 1.7 times faster than population growth [2]. Besides population growth, intensified climate change and recent virus outbreak may worsen water scarcity and affect food security, human health, energy production and biodiversity [3]. Sustainable Development Goals (SDGs) that were introduced in 2018 target the provision of sufficient clean water for 2.2 billion people and proper sanitation for 4.2 billion people [4]. To ensure humans receive sufficient water, improvement in wastewater treatment to allow for reclamation may become a crucial approach.

Conventional wastewater treatment mainly relies on biological treatment processes. Undeniably, conventional wastewater treatment manages to remove most pollutants such as BOD and COD with average removal more than 95% [5;6]. However, critical disadvantage of this conventional treatment is low pathogens removals, which make it unsuitable for wastewater reclamation [7]. Various studies carried out on pathogen removal from conventional wastewater treatment plant show that it is unable to reduce pathogen levels to comply with US.EPA standards [8-10]. Of the studied wastewater treatment plants, most did not comply with standards, having recorded various pathogen species removal of less than 50% [10;11].

Identification of additional treatment that can be coupled with conventional wastewater treatment is important to overcome critical disadvantage of the current treatment method. Among many additional treatments, slow sand filter (SSF) is the most effective. Not only it is a cost-effective treatment, its use of less energy-intensive technology and less dependency on chemicals and skilled labour make it a sustainable wastewater treatment process [12]. SSF treat wastewater by trapping contaminants in the sand column and the resultant filtrate will then flow out into drain collection for storage and distribution [13]. Periodically, sand column needs to be cleaned. Cleaning SSF does not require backwashing like rapid sand filter (RSF). Over the years, sand layer must be replaced to ensure the optimum depth can be achieved for optimum contaminant removal [14].

Previous study has proven that SSF have higher pathogen removal efficiency compared to biological treatment. In a study by Mulugeta *et al.* [15], SSF applied on municipal wastewater shows removal of total coliform and fecal coliform exceeding 99%, while study by Bagundol *et al.* [16] shows 98% E. Coli removal on raw water from a deep well. The mechanism responsible for high pathogen removal is layer of microbes such as protozoa, bacteria and algae known as filter skin or *schumtzdecke* layer. Sand column will trap pathogens from wastewater that passed through and *schmutzdecke* layer will break down the pathogens probably as food sources [17].

Besides this mechanism, a few additional factors such as sand bed depth, filtration rate and others play an important role in successful contaminant removal not limited to pathogens by

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using SSF [18-22]. Therefore, objectives of this study are to determine the effect of sand media depth on the removal efficiency of the sand filter and to study the effect of sand media depth on the volume flow rate for the sample to pass through the sand filter.

2 Materials and Methods

2.1 Samples Collection

The sand filtration experiments were performed at Centre for Environmental Sustainability and Water Security where separate different sand bed depth of slow sand filtration systems were operated for research purposes. The collected samples were effluent from local sewage treatment plant (STP). The samples were collected three times at three different dates. The effluent discharge complies with Standard B based on the Environmental Quality (Sewage) Regulations 2009 and Class IIA in National Water Quality Standard (refer Table 1).

Table 1: Standard B (a) and Class IIA (b)

Parameters	**Unit**	**Value**
Biochemical oxygen demand (BOD)	mg/L	50[a]
Chemical oxygen demand (COD)	mg/L	200[a]
Suspended solids	mg/L	100[a]
Turbidity	NTU	50[b]

2.2 Experimental Setup

The sand filters were designed in three different depths to study the effect of sand depth in removal efficiency of the filter. The materials used to construct the sand filters were PVC pipes, which were 0.51 cm thick and have a 7.62 cm inner diameter, sand that can pass through sieve with opening size 0.85 mm, gravel that was 20 mm in diameter, rubber tube, mesh and cotton wool. The PVC pipe caps were mounted on the bottom of the sand filters and three holes were drilled at the bottom of the caps. After installation of the PVC cap, the cotton wool and mesh were put inside the filters to prevent the sand from washing out from the filters. The three different lengths of filters were filled with 10 cm gravel in each filter. Then, the three filters were filled with 30 cm, 60 cm and 90 cm of sand, respectively. Figure 1 shows the illustration of sand filter. The details of three sand filters were summarised in Table 2.

During filtration process, the flow rate of sample passed through the filter was determined. A total of 5L of sample was used for every filter. The time for 5L of sample to pass through the filter was measured by using stopwatch. The formula used to calculate the volume flow rate is as in Eq. (1).

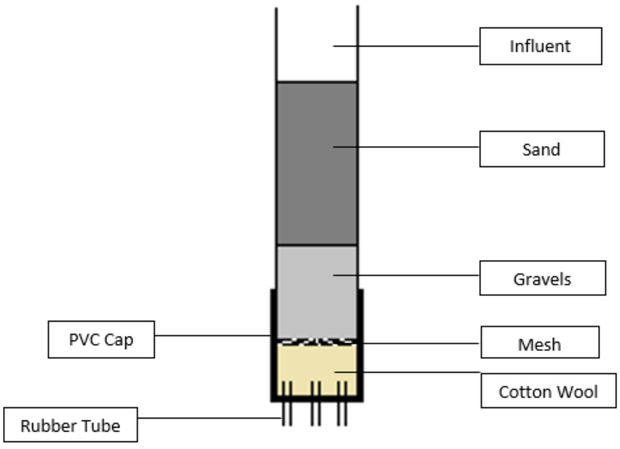


Figure 1: Illustration of the sand filter

Table 2: Details of the sand filters

Parameters	**Sand Filter 1**	**Sand Filter 2**	**Sand Filter 3**
Gravel depth, cm	10	10	10
Sand depth, cm	30	60	90
Standing water height, cm	18	18	18
Pipe inner diameter, cm	7.62	7.62	7.62
Total sand filter height, cm	60	90	120

$$\text{Flow rate}\left(\frac{\text{L}}{\text{min}}\right)=\frac{\text{5 L of sample}}{\text{Time for sample passed through filter}} \quad (1)$$

2.3 Analytical Method

In this study, turbidity was measured using HACH 2100Q Portable turbidimeter. Total suspended solids (TSS) and biochemical oxygen demand (BOD) was determined based on standard method APHA 2540 D and 5210 B, respectively. Chemical oxygen demand (COD) of the sample was determined based on USEPA Reactor Digestion Method. Both total coliform and E. Coli were determined based on APHA 9223 Colilert.

3 Results and Discussion

3.1 Characteristics of Treated Sewage

Effluent from local STP was used as sewage sample for the sand filtration process. Characteristic of the effluent is shown in Table 3. Based on Table 3, the average turbidity, BOD, COD and suspended solids are 22.3 NTU, 18.3 mg/L, 93.7 mg/L and 14.8 mg/L, respectively. Inconsistent reading of the parameters may be due to weather condition during the day of sampling. By referring to Environmental Quality (Sewage) Regulations 2009, the treated sewage is safe to be released into the water body. For a sewage to be released into water body, it needs to comply with at least standard B of these regulations. By referring to Standard B of this regulation, recorded BOD, COD and suspended solid should be below 50 mg/L, 200 mg/L and 100 mg/L. Meanwhile, according to National Water Quality Standards (NWQS), recorded turbidity of average 22.3 NTU comply with Class IIA, which is suitable for conventional water treatment. Therefore, based on both standards, the treated sewage is safe by referring to its turbidity, COD, BOD and TSS, but the recorded total coliform and E. Coli is quite high similar to the claim by previous study that conventional wastewater treatment has low pathogen removal rate.

Table 3: Characteristics of the collected sample

Parameter	**Sample 1**	**Sample 2**	**Sample 3**	**Ave.**
Turbidity (NTU)	25.3	24.0	17.6	22.3±4.1
BOD (mg/L)	13.1	22.5	19.2	18.3±4.8
COD (mg/L)	42.1	124	115	93.7±44.9
TSS (mg/L)	10	19	15.3	14.8±4.5
T.Coliform (MPN)	>2419.6	>2419.6	>2419.6	2419.6±0
E.Coli (MPN)	>2419.6	>2419.6	>2419.6	2419.6±0

3.2 Effect of Sand Depth in Filter towards Filtrate Flow Rate

Figure 2 shows the profile filtrate of flow rate for distilled water (as control and three other samples) based on different filter bed depth.

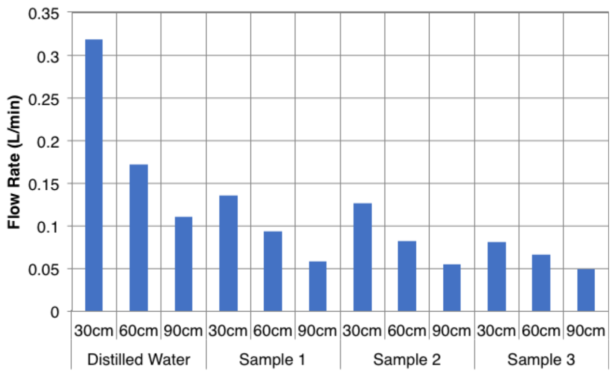


Figure 2: The filtrate flow rate for every sample

Based on Figure 2, the filtrates of distilled water have a higher flow rate than sample 1, 2 and 3. Distilled water does not contain many impurities and contaminants which can slow down the flow rate. Meanwhile, all three (3) sewage samples shows lower flow rate compared to distilled water but with similar pattern, where the highest flow rate was recorded in filter with 30 cm sand depth and lowest flow rate was recorded in filter with 90 cm sand depth. Based on this result, it can be concluded that the flow rate will decrease when the sand depth in filter increase as higher sand depth will increase the contact time between sewage samples with the sand grains.

3.3 Impurities within Different Sand Filter

The three sand filters with different sand depth are filtered by distilled water to determine the impurities inside the sand. The result of the impurities presence in the filters are shown in Table 4. Based on Table 4, filter with 90 cm sand depth has the highest turbidity, COD, and BOD value, which is 14.9 NTU, 176 mg/L and 65.6 mg/L, respectively. This indicates that the composition of impurities inside the 90 cm sand depth filter is higher than other filters due to 90 cm sand depth filter contains more sand grains than other filters and thus have more impurities. However, for the TSS, sand filter with 30 cm sand depth has the highest value among others.

Table 4: Properties of impurity within sand filter of different depth

Parameter	**30 cm**	**60 cm**	**90 cm**
Turbidity (NTU)	4.23	12.1	14.9
COD (mg/L)	89	153	176
BOD (mg/L)	36.45	55.95	65.55
TSS (mg/L)	16.03	12.4	12.5
T.Coliform (MPN)	>2419.6	>2419.6	>2419.6
E.Coli (MPN)	1.0	<1.0	<1.0

Based on Table 4, filter with 90 cm sand depth has the highest turbidity, COD, and BOD value, which is 14.9 NTU, 176 mg/L and 65.6 mg/L, respectively. This indicates that the composition of impurities inside the 90 cm sand depth filter is higher than other filters due to 90 cm sand depth filter contains more sand grains than other filters and thus have more impurities. However, for the TSS, sand filter with 30 cm sand depth has the highest value among others.

3.4 Effect of Sand Filter Bed Depth on Pathogen Removal

Figure 3 shows the count of total coliform before and after filtration and its removal efficiency by using different sand bed depth.

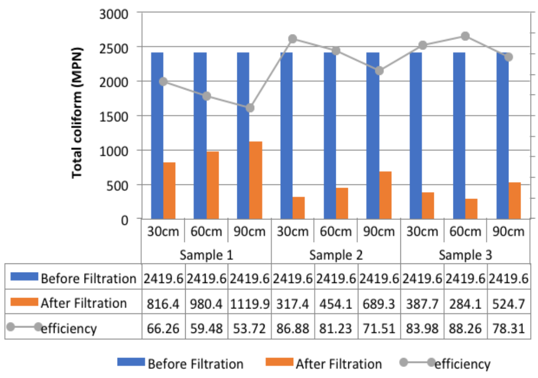


Figure 3: Total Coliform count before and after filtration

Based on Figure 3, sample passed through every filter shows reduction in the concentration of total coliform. Filter with 30 cm sand depth shows the highest total coliform removal in sample 1 and sample 2, but sample 3 shows highest total coliform removal by using 60 cm sand depth. Total coliform concentration drops from >2419.6 MPN to 816.4 MPN in sample 1 and from >2419.6 MPN to 317.4 MPN in sample 2 by using filter with 30 cm sand depth. However, in sample 3, the highest total coliform removal, from >2419.6 MPN to 284.1 MPN, occurs in the filter with 60 cm sand depth. Generally, filter with 30 cm sand depth shows higher removal efficiency than filters with 60 cm and 90 cm sand depth. In sample 1 and 2, filter with 30 cm sand depth achieved 66.3% and 86.9% removal efficiency, respectively, but in sample 3, the highest removal efficiency was achieved by using filter with 60 cm sand depth which is 88.3%. On the other hand, filter with 90 cm sand depth has lowest removal efficiency, which are 53.7%, 71.5% and 78.3% for sample 1, 2 and 3, respectively. This may due to additional of coliform that exist in the sand granules itself. Higher sand depth will expose more of the sewage sample to the sand granules, which not only remove the total coliform but also add some to the filtered sewage. This data is in accordance to previous study where the recorded total coliform removal increased from 95% to 97% by decreasing the sand depth from 0.97 m to 0.48 m [21].

Figure 4 shows the E. Coli concentration of the sewage before and after filtration and its removal efficiency by using different sand bed depth. Based on the graph, filtration process of various depths manages to drastically decrease the E. Coli concentration in the sample sewage. Similar to total coliform removal, 30 cm sand depth managed to remove the most E. Coli in the sewage compared to 60 cm and 90 cm sand depth. However, the differences are not that significant. By using filter with 30 cm sand depth, the E. Coli concentration decrease drastically from >2419.6 MPN to 123.6 MPN, 116.7 MPN and 108.2 MPN for sample 1, 2 and 3, respectively, with average removal efficiency of 95.5%.

Meanwhile, by using filter with 90 cm sand depth, the E. Coli concentration also decrease drastically from >2419.6 MPN to 167.1 MPN, 131.8 MPN and 139.2 MPN for sample 1, 2 and 3, respectively, with average removal efficiency of 94.0%. This occurrence may be due to presence of protozoa, bacteria, algae and other forms of life within the filter bed which contribute to removal of pathogens and other pollutants in the filtrate [16].

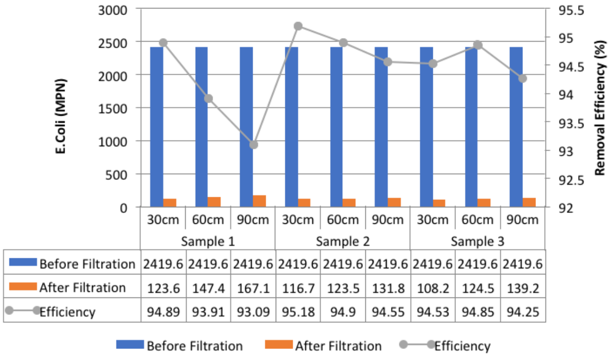


Figure 4: E. Coli count before and after filtration

3.5 Effect of Sand Filter Bed Depth on Turbidity Removal

Figure 5 shows the recorded turbidity of sewage before and after filtration and its removal efficiency by using different sand bed depth.

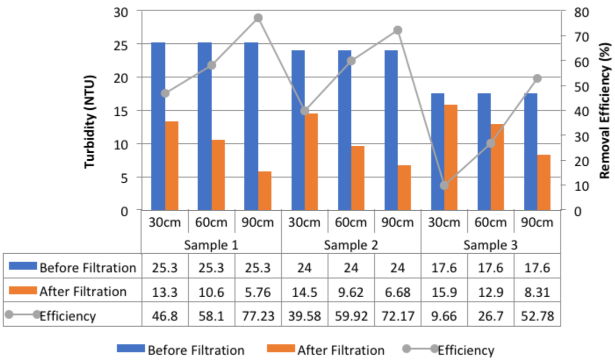


Figure 5: Turbidity of the sample before and after filtration

Based on Figure 5, 90 cm sand depth shows highest turbidity removal which is not similar to total coliform and E. Coli removal where 30 cm sand depth shows better removal. Sample 1 shows highest turbidity removal by using 90 cm sand depth by reducing the turbidity to 5.76 NTU from 25.3 NTU. Meanwhile, by using filter with sand depth of 30 cm, the turbidity is reduced to 8.31 NTU from 17.6 NTU. Based on this data, it can be seen that filter with 90 cm sand depth shows more significant decrease in turbidity followed by 60 cm and 30 cm sand depth with average removal efficiency of 67.4%, 48.2% and 32.0%, respectively. It can be concluded that the removal efficiency will increase when the sand bed depth increase as more particulate matter will be retained in the filtration bed [23].

3.6 Effect of Sand Filter Bed Depth on Total Suspended Solids Removal

Figure 6 shows the recorded TSS before and after filtration process and its removal efficiency by using different sand bed depth. Based on Figure 6, it is shown that sand filter can significantly reduce the suspended solids content in the sewage sample. Among the three (3) different filters with different sand depth, filter by using 90 cm sand depth shows greater removal followed by filter using 60 cm and 30 cm sand depth. The removal trend is similar to the turbidity removal. Filter by using 90 cm sand depth shows a decrease from 10 mg/L to 1 mg/L in sample 1, from 19 mg/L to 1.7 mg/L in sample 2 and from 15.3 mg/L to 2.2 mg/L in sample 3.

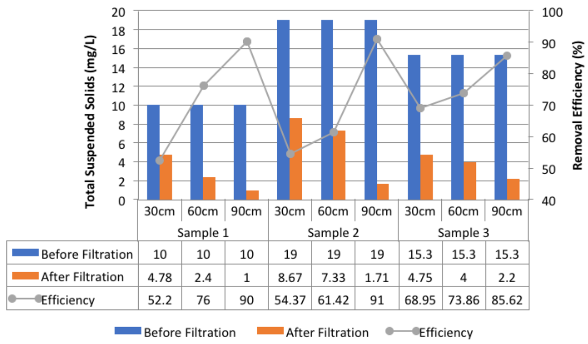


Figure 6: TSS before and after filtration

However, filter with 30 cm sand depth shows lesser suspended solids removal compared to the other two filters. The 30 cm sand depth filter only shows a decrease of 5.2 mg/L, 10.3 mg/L and 10.6 mg/L in sample 1, 2 and 3, respectively. Filter with 90 cm sand depth shows better TSS removal with average removal efficiency of 88.9% followed by 60 cm sand depth and 30 cm sand depth with average removal efficiency of 70.4% and 58.5%, respectively. It can be concluded that TSS removal efficiency is similar to turbidity removal where higher sand depth will result in higher TSS removal as higher sand depth can increase solid retention and thus improve the removal efficiency [24].

3.7 Effect of Sand Filter Bed Depth on COD Removal

Figure 7 shows COD concentration in the sewage samples before and after filtration by using various sand depth and its removal efficiency.

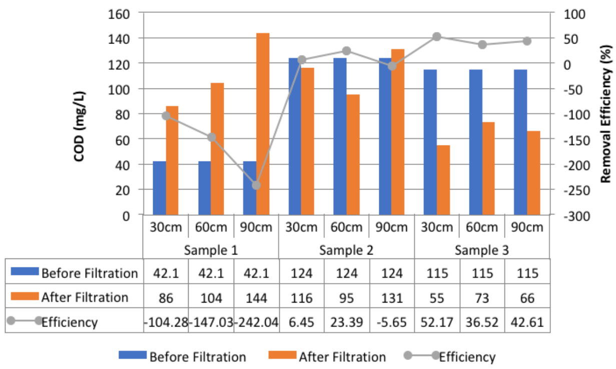


Figure 7: COD concentration of sample before and after filtration

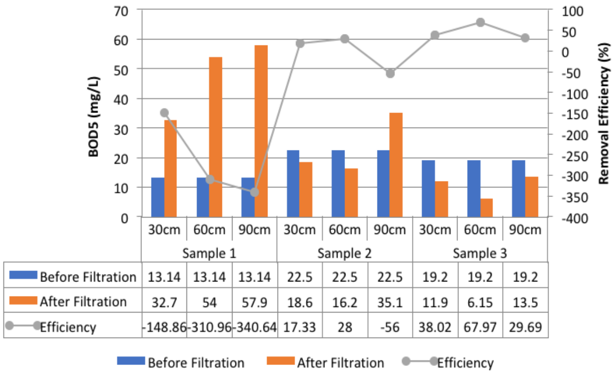
Based on Figure 7, sample 1 after filtration shows a negative COD removal. COD concentration of sample 1 after filtration has increased from 42.1 mg/L to 43.9 mg/L, 61.9 mg/L and 101.9 mg/L for 30 cm, 60 cm and 90 cm sand depth, respectively. This condition is due to the presence of contaminants inside the sand grains that contribute to COD concentration as shown in Table 3. Higher sand depth will lengthen the exposure of the sewage samples to the contaminated sand grains.

However, in sample 2, filters decrease COD concentration of samples from 124 mg/L to 116 mg/L and 95 mg/L by using 30 cm and 60 cm sand depth, respectively. The filter with 90 cm sand depth still shows a negative removal at which the COD concentration after filtration has increased by 7 mg/L, but the increment of COD after filtration has been decreased compared to the COD concentration after filtration in sample 1. On the other hand, filter with 30 cm on sample 3 shows the best COD removal ability followed by filter with 90cm and 60 cm sand depth that reduce COD concentration from 115 mg/L to 55 mg/L, 66 mg/L and 73 mg/L, respectively. All three filters show a positive COD removal. The increment of the removal efficiency from negative to positive indicates that the contaminants inside the filter have been washed out along with the filtrate. Thus, the loss of contaminants in the filter will result in positive removal efficiency.

3.8 Effect of Sand Filter Bed Depth on BOD Removal

Figure 8 shows the BOD concentration of samples before and after filtration using various sand depth and its removal efficiency. Based on the bar chart, BOD concentration shows a significant decrease for three filters in sample 3. Filter with 30 cm, 60 cm and 90 cm sand depth show decrease in BOD from 19.2 mg/L to 11.9 mg/L, 6.15 mg/L and 13.5 mg/L, respectively.

On the other hand, sample 1 shows increment in BOD concentration in all three (3) different sand depths. Filter with 30 cm, 60 cm, and 90 cm increase BOD concentration from 13.1 mg/L to 32.7 mg/L, 54 mg/L and 57.9 mg/L, respectively. BOD removal for sample 2 is similar to COD removal where only 90 cm sand depth shows BOD removal from 22.5 mg/L to 35.1 mg/L, but 30 cm and 60 cm sand depth manage to reduce BOD from 22.5 mg/L to 18.6 mg/L and 16.2 mg/L, respectively. Based on the data, it can be concluded that filter with more sand granules will either be unable to reduce BOD or be able to reduce only a small portion of it. This is because during filtration, contaminants that contribute to BOD concentration are washed out along with the collected filtrate.



	30cm	60cm	90cm	30cm	60cm	90cm	30cm	60cm	90cm
	Sample 1			Sample 2			Sample 3		
Before Filtration	13.14	13.14	13.14	22.5	22.5	22.5	19.2	19.2	19.2
After Filtration	32.7	54	57.9	18.6	16.2	35.1	11.9	6.15	13.5
Efficiency	-148.86	-310.96	-340.64	17.33	28	-56	38.02	67.97	29.69

Figure 8: BOD concentration of sample before and after filtration

3.9 Comparison of the removal efficiency of filter at different sand depth

Figure 9 shows the removal efficiency of the filters with different sand bed depth in every parameter tested for three samples. Overall, the filter with 90 cm sand depth has higher efficiency in removing turbidity and TSS as higher sand depth is able to retain more solids that contribute to turbidity and TSS. Meanwhile, filter with 30 cm sand bed depth is more efficient in the removal of total coliform and E. Coli because higher sand depth exposes the treated sewage to the existing coliform in the sand granules and is washed out together with the filtrate. On the other hand, sand filter shows ineffective COD and BOD removal as both shows increase in sample 1 while very low removal in sample 2 and 3. Retained contaminants in the sand layer decompose slowly which in turn release organic matter in term of Dissolved Organic Carbon (DOC). Released DOC into the effluent increased the COD and BOD content [25]. Based on Figure 9, 90 cm sand filter have higher COD content in the effluent as it retained more contaminant which later decomposed and release more organic matter. Based on previous studies, it is stated that the mechanism that makes successful SSF is the *schmutzdecke* layer. However, in this study, no time was provided for *schutzdecke* layer formation, thus using bed depth as variable alone manages to remove pathogens exceeding 80%, which is good enough to be coupled with conventional wastewater treatment.

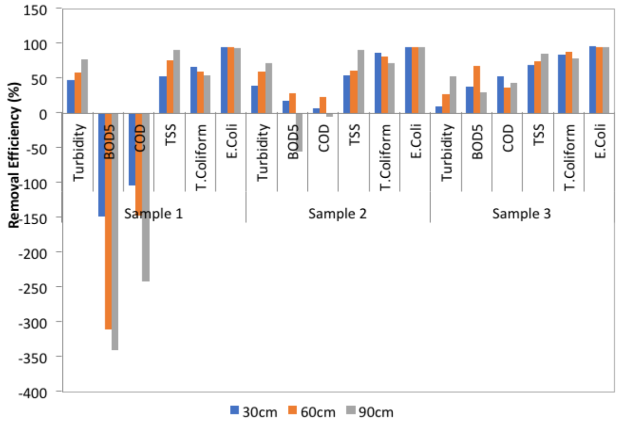


Figure 9: Comparison of the removal efficiency of the filter with different sand bed depth

4 Conclusions

In conclusion, the sand bed depth has effect on the removal efficiency and flow rate of the filter. The removal of TSS, turbidity, BOD, COD, total coliform and E. Coli are varied at different sand bed depth. The sand filter is more efficient in removing the suspended contaminants and the coliforms compared to the dissolved contaminants. Removal of turbidity and TSS by using the 90 cm sand depth filter is more effective compared to others. This shows that higher sand bed depth will result in higher removal efficiency of the filter in removing turbidity and TSS. For the removal of total coliform and E. Coli, filter with 30 cm sand bed depth show a good efficiency. The BOD and COD concentration presence in the sand are too high, which cause the removal efficiency to become negative. Filtration process alone is insufficient to properly remove COD and BOD. In addition, the different sand bed depths also affect the flow rate of the sample to pass through the filter which will affect the volume of filtrate obtained. In general, higher sand bed depth results in lower flow rate to pass through the filter. This is because the percolate particles in the sample undergo longer interaction with the sand grains to remove the contaminants.

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Ethical issue

Authors are aware of, and comply with, best practice in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language.

Competing interests

The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

Authors' contribution

All authors of this study have a complete contribution for data collection, data analyses and manuscript writing.

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