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Research paper

Integrated treatment of stormwater using multistage filtration (MSF) for domestic application (reuse)

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Stormwater harvesting is a promising solution for global freshwater depletion, particularly in tropical regions with abundant rainfall. However, it is not widely used due to the lack of suitable treatment technologies for domestic applications. Multi-stage filtration (MSF) is an effective integrated treatment technology that provides a cost-effective alternative for stormwater treatment. This study investigated MSF's capacity for treating stormwater at different stages. The MSF designed and built comprised the down-flow roughing filter (DRF) and slow sand filter (SSF). The results achieved by the MSF for the treated effluents were: pH (7.1–8.1), temperature (27.6–29.4°C), electrical conductivity (EC) (100–190 µS/cm) and total dissolved solids (TDS) (70–130 mg/L). Turbidity removal efficiency of the MSF was in the range of 36–99% (5.825–164.05 NTU) and the overall average removal efficiency of the MSF was 74%, 90% and 86% for total coliforms (TC) (360–11 800 CFU/100 mL), faecal coliforms (FC) (0–1 300 CFU/100 mL) and *Enterococcus* spp. (120– 1 400 CFU/100 mL), respectively. The study identified stormwater reuse potentials based on international guidelines and benchmarks. For the treated effluent, pH, temperature, EC and TDS were all within the permissible limits for toilet, laundry, bathing, recreational and agricultural water reuse, while turbidity suited agricultural (non-food crop) and restricted urban reuse. 46% of the effluent was suitable for recreational purposes as this satisfied the 50 NTU standard. 62.5% of the effluent satisfied the FC standard for toilets and urinals and agricultural reuse (non-food crop) purposes, while 87.5 % of the effluent satisfied urban reuse purposes (restricted access). 66.67% of the effluent satisfied the *Enterococcus* spp. standard for agricultural reuse (non-food crop). All treated effluents satisfied the TC bathing standard. This study shows that after minimal disinfection, stormwater effluents offer potential reuse in household applications, thereby reducing potable water demand.

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INTRODUCTION

Worldwide, there is increasing demand for available freshwater resources because of increasing population and urbanization (Hatt et al., 2005; Yang and Cui, 2012; Barasa and Asaba, 2020; Rahman et al., 2014; Amin and Alazba, 2011; Awawdeh et al., 2012). The current water scarcity situation is anticipated to get worse in the face of global warming and climate change (Nnadi et al., 2015). An estimated 839 million or 11% of the world's population are without clean water and global water demand is expected to double by 50% in 2030 (WHO and UN-Water, 2017). Sub-Saharan Africa ranks lowest in the world for access to improved drinking water and sanitation (WHO and UN-Water, 2017) with Nigeria being one of the 15 countries in Sub-Saharan Africa suffering from water scarcity and stress (Ogunbiyi, 2012). This has led to the prevalence of water-related disease, especially among rural communities, with more than 80 000 water-related deaths yearly (WHO, 2020; WHO, 2014). With the increasing pressure on freshwater reserves and the burgeoning population, Nigeria's water scarcity situation calls for the need to manage water resources more sustainably. To this end, the treatment and beneficial reuse of stormwater runoff is in Nigeria's national interest.

Treatment and reuse of stormwater runoff are receiving increased attention worldwide as an alternative source of water supply, and have become a practical solution to the problem of water scarcity in many countries (NASEM, 2016; Amin and Han, 2009b; Ibrahim, 2009; Yang and Cui, 2012). This practice is increasing in developing countries like China and India which are highly urbanized but are experiencing water scarcity. They concentrate on harvesting the maximum volume of runoff from urban areas with little regard for water quality. Even in developed countries like Australia with large cities suffering water shortages, harvesting of stormwater runoff is widely practised at both the local and regional levels, with technologies for full-scale stormwater treatment at their disposal (Kus et al., 2012; Petterson et al., 2016). Many studies have revealed that stormwater runoff, although influenced by varying catchment and rainfall characteristics, has common pollutants that have been generally categorized as sediment, toxic chemicals, hydrocarbons, nutrients, heavy metals and organic matter (Pal, 2012; Aryal et al., 2010; Egodawatta, 2008). Treatment and removal of these pollutants can be achieved in three hierarchical stages: primary, secondary and tertiary treatment. To widen the reuse potential of stormwater runoff, a higher level of treatment and purification of water will be required. Generally, different stormwater treatment processes are combined to reduce pollutants to provide the best overall treatment efficiency, but this may not be feasible in every situation due to the problems of cost and expertise. Rather, one or two unit operations or processes that have a high capacity for water quality improvement can be selected.

Due to a lack of treatment technologies for stormwater runoff, rural and water-stressed communities of Africa mainly practice rooftop rainwater harvesting, which cannot be completely relied upon because it ends with the rainy period and does not take care of all their water demand. This deficiency is particularly acute when water demand increases to a full connection level, even in the rainforest zone with an abundance of rainwater (Nnaji and Mama, 2014). Alternative sources of water supply improvement, such as seawater desalination and wastewater treatment and reuse, are capital-intensive and may not be within the financial and technical capacity of developing countries (Hamdan, 2009). Stormwater has a greater capacity to meet the domestic water demand due to its superior quality when compared with industrial discharge or untreated wastewater (Mitchell et al., 2002), and also has a better public tolerance for usage. Besides curbing water challenges, stormwater harvesting provides other benefits, such as mitigation of flood/erosion through the reduction of stormwater volume, and protection of waterways and receiving waters from increased pollutant load from stormwater (NASEM, 2016; Kus et al., 2012; Dandy et al., 2019).

Although Nigeria has no national programme for the promotion of stormwater runoff harvesting, the practice has been around for years as a traditional source of domestic water supply, especially among rural communities in the semi-arid northern part of the country (Nyong and Kanaroglou, 1999; Lombin et al., 1986). Detention ponds or pools are dug close to residents or in river beds for the collection of stormwater runoff. Such ponds can outlast ephemeral rivers and hold water well into the dry season or year-round, depending on the geographic location and subsoil conditions. The only treatment provided in such ponds is gravity settling/sedimentation, in which particles with a specific gravity higher than 1 settle out under quiescent conditions. Because stormwater particles are relatively large with a specific gravity ranging from 1.5 to 3.0 (Li et al., 2006), sedimentation can be very effective for the removal of sediment-associated pollutants from stormwater runoff (Clark and Pitt, 2012). Pond water is used for bathing and watering livestock, as well as drinking under water crisis conditions (Gogoi and Sharma, 2013).

A study by Friedman (2012) revealed that, globally, the current household water demand per capita is in the range of 5.4–575 L/day, with 45%, 30%, 20% and 5% used for flushing, bathing, laundry and cooking, respectively. Among other domestic uses of water, the volume of water required for drinking is the least. Pan et al. (2018) affirmed that the basic daily requirement per person is 1–1.5 L. The reuse of stormwater for other non-potable purposes, which is well-accepted in many countries (Lazarova et al., 2003), will reduce the burden on drinking water. Due to the low level of treatment adopted in this study, the potential reuse options for the treated water are urinal and toilet flushing, agricultural and irrigation purposes (irrigation of lawns, planting of food crops and non-food crops), bathing, restricted urban reuse (washing of vehicles and windows, fire protection, dust control, concrete production, develop and preserve wetlands, industrial reuse). Many developed countries have established and published various guidelines and legislation covering wastewater/water reuse for different purposes, but very few developing countries have done so. Some of these international guidelines and standards were used as our basis of comparison and acceptance for appropriate reuse purposes.

This present study adopted and evaluated the efficiency of sedimentation and multistage filtration (MSF) for the treatment of stormwater runoff (NASEM, 2016). Multistage filtration (MSF) is an integrated water treatment method that has been proven to be sustainable and robust, addressing many drawbacks associated with the conventional slow sand filtration method. Multistage filtration provides several layers of filters against pollutants, comprising of pre-treatment by coarse gravel media (especially roughing filters) before the main slow sand filtration (Cleary, 2005; Galvis, 1999). MSF systems outperformed conventional systems in turbidity removal and can achieve more than 99% bacteriological quality improvement (Ochieng et al., 2004). MSF holds enormous promise for the water quality challenges in developing countries (Nabwayo, 2016; Ochieng et al., 2004).

Using practical experience from other countries where this technology has been practised, this research aimed to design and test the performance of MSF units in treating stormwater. MSF is still not well recognized and commonly used in Nigeria, hence it was needful to design a pilot MSF system (combining downflow roughing filter and slow sand filter) and explore its performance in treating variable raw water quality like stormwater runoff. The detailed objectives were to:

- Characterize stormwater samples
- Subject characterized stormwater samples to an integrated sequence of treatments, viz: sedimentation, downflow, roughing filter and slow sand roughing filter and determine their performances
- Determine the efficiency of the entire MSF unit in removing turbidity and microorganisms from stormwater with high turbidity levels
- Compare the treated effluents with different water reuse guidelines and standards to determine its most suitable reuse potentials

MATERIALS AND METHODS

Raw water samples used for the experimental work were collected from drains located at the intersection between University Road and University Market Road, Nsukka, Nigeria, during or immediately after rainfall events. This location was strategically chosen because it captures runoff contributed by the upland areas of Nsukka, which includes the major industrial, commercial and residential part of Nsukka, and therefore must have accumulated pollutants that reflect the true stormwater runoff characteristics of the town.

Experimental setup and filter configuration

The treatment system consists of a sedimentation unit, a downflow roughing filter unit and a slow sand filter unit connected in series (Fig. 1). The system was arranged to allow water flow by gravity. Water flows from the sedimentation unit through the top of the roughing filters before entering the top of the slow sand filter. The sedimentation unit was made of a polyethene plastic cylindrical tank (Geepee tank) with a capacity of 700 gallons (2 650 L), 1 240 mm in diameter and 1 740 mm in height. The purpose of this unit was to simulate the settling processes of a detention pond by providing a quiescent condition for settleable suspended solids to settle out. Sedimentation can reduce turbidity and make the water more amenable to filtration and other treatment methods.

The down-flow roughing filter unit was made of 3 polyvinyl chloride (PVC) columns of heights 1.675 m, 1.415 m and 1.320 m, connected in series as shown in Fig. 1. Each column had the same internal diameter of 152.4 mm. Quartz was used as the roughing filter medium. The characteristics of the filter media are shown in Table 1. The roughing filters were labelled R_1, R_2 and RF in Fig. 1 for ease of reference. The sampling points used for assessing the performance of the roughing filter are identified on the roughing filters (R_1, R_2 and RF) in Fig. 1 as Points a, b and c. Wegelin (1996) design criteria were used as a guide in selecting the design parameter for the roughing filter. In the selection of the sizes of the filter media used, the quality of the raw water was a major consideration. The filter media were thoroughly washed with clean water and air-dried before use.

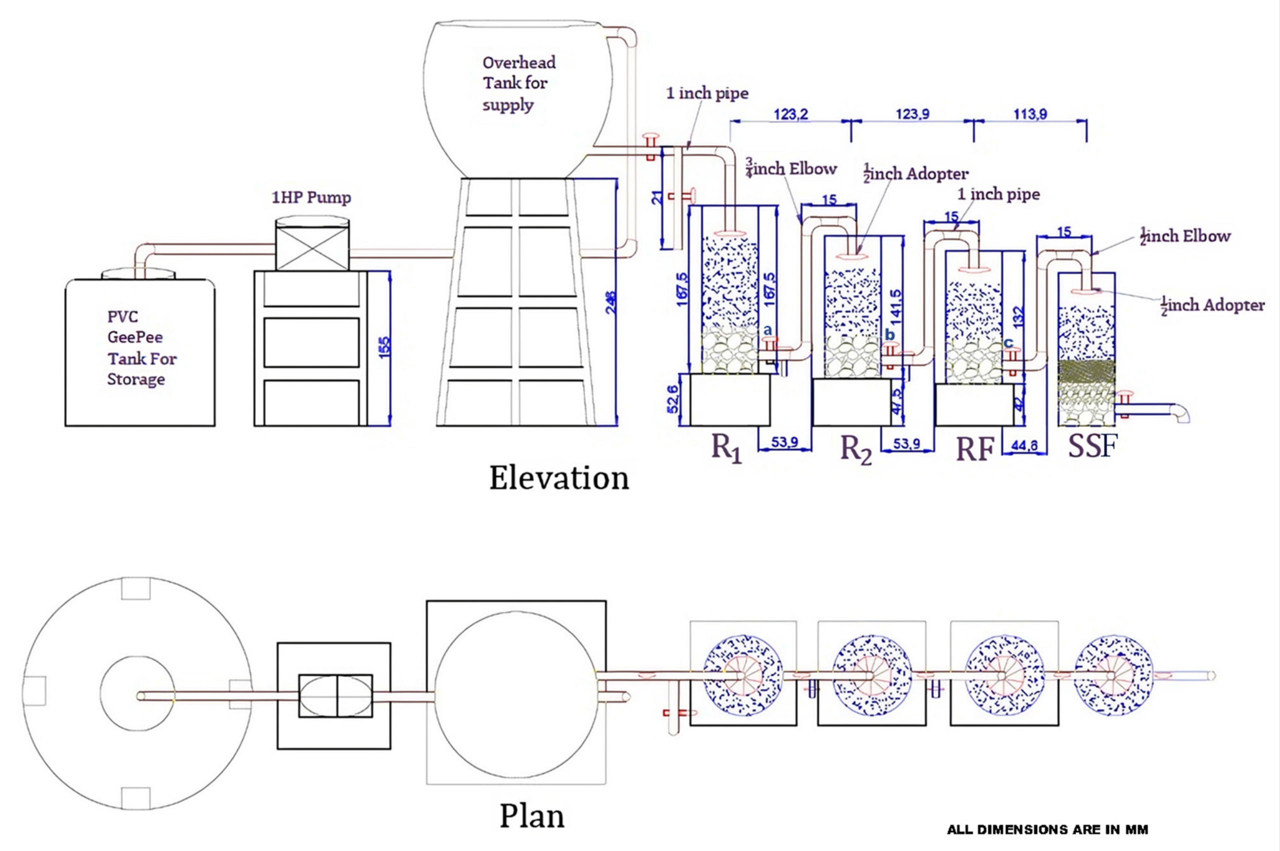


Figure 1. General layout of the experimental setup (multi-stage filtration system); slow sand filter unit is designated SSF

Table 1. Characteristics of the filter media

Design parameter		Literature recommendation	Design parameter used
Filter media size (mm)	Column R_1	8–12	9.52–12.70
Filter media size (mm)	Column R_2	4–8	4.76–9.52
	Column RF	2–4	2–4.76
Filter media depth (m)	Column R_1	0.6–1.0	0.8
Filter media depth (m)	Column R_2	0.6–1.0	0.8
	Column RF	0.6–1.0	0.6
Filter media type		Quartz	Quartz
Flowrate			Varied
Underdrain size (mm)			4.76–19.05
Height of underdrain (mm)			0.3

The slow sand filter unit was also built with PVC pipe of diameter 152.4 mm and a height of 1.52 m. Sieve analysis was carried out on the filter media to determine the grain size distribution and uniformity coefficient before filling the column. The PVC pipe was filled to a depth of 0.3 m with quartz of diameter range 4.76–19.05 mm as the underdrain. The fine sand layer, of thickness 0.8 m, effective diameter 0.14 and uniformity coefficient 2.71, was placed on top of the underdrain. Sampling points were located at the outlet of the unit so that removal efficiency could be monitored. Design and sizing of the SSF unit was carried out based on the recommended guideline in the design manual (Galvis et al., 1998; Wegelin, 1996)

Experimental design and operation

The experiment was designed to investigate the efficiency of the MSF in treating stormwater runoff. Performances of the filtration units were monitored by measuring flow rate, and collecting and analysing water samples from the designated sampling points of the filtration units. A total of 13 batches of filter runs (A, B, C, D, E, F, G, H, I, J, K, L and M) were conducted (Table 2) between September and December 2019.

Water quality analysis

Filtrates were collected from the outlets provided near the bottom of the raw water supply tank, roughing filtration unit and slow sand filtration unit of the multistage filtration system. The samples were analysed for pH, total dissolved solids (TDS), temperature, electrical conductivity (EC), turbidity, total coliforms (TC), faecal coliforms (FC) and *Enterococcus* spp. (Table 3). A PH-116 multi-parameter water quality monitor was used in determining pH, temperature, total dissolved solids and electrical conductivity of the raw water samples and effluents from filters. The accuracy

Table 2. Experimental schedule

Batch	Experimental schedule	Filtration rate (m/h)	Hydraulic residence time (HRT) (h)
A	2019/10/24 (Thu) – 2019/10/25 (Fri)	0.0042	76.190
B	2019/10/30 (Wed) – 2019/10/31 (Thu)	0.2025	1.580
C	2019/11/04 (Mon) – 2019/11/05 (Tue)	0.2729	1.173
D	2019/11/06 (Wed)	0.9997	0.320
The filter media were removed washed and sun/air-dried after observing a decrease in effluent quality	2019/11/09 (Sat) – 2019/11/10 (Sun)		
E	2019/11/14 (Thu)	0.9997	0.320
F	2019/11/14 (Thu) – 2019/11/15 (Fri)	0.1270	2.520
The systems began to leak seriously after washing and replacing the filter media so it was out of operation for repair between16 and 19 November 2019	2019/11/16 (Sat) – 2019/11/19 (Tue)		
G	2019/11/21 (Thu) – 2019/11/22 (Fri)	0.2308	1.386
H	2019/11/25 (Mon) – 2019/11/26 (Tue)	0.0849	3.769
I	2019/11/28 (Thu) – 2019/11/15 (Fri)	0.0874	3.661
J	2019/11/29 (Fri) – 2019/11/30 (Sat)	0.0522	6.130
K	2019/12/03 (Tue) – 2019/12/04 (Wed)	0.0175	18.286
L	2019/12/05 (Thu) – 2019/12/06 (Fri)	0.0158	20.253
M	2019/12/11 (Wed) – 2019/12/12 (Thu)	0.1257	2.546

Table 3. Water quality analyses

Water parameter	Batches
pH	A, B, C, D, E, G, H, I, J, K, L, M
Temperature	H, I, J, K, L, M
Electrical conductivity	A, B, C, D, E
Total dissolved solids	A, B, C, D, E,
Turbidity	A, B, C, E, F, G, H, I, J, K, L, M
Total coliforms	A, B, E, G, H, I, J, K, L, M
Faecal coliforms (*E.coli*)	A, B, E, G, H, I, J, K, L, M
Enterococcus spp.	A, B, E, I, J, K, L, M

of the pH was ± 0.1; temperature ± 1°C; electrical conductivity ± 2% EC. Turbidity was determined using the HACH model 2100N laboratory turbidity meter which is designed to measure 0–4 000 NTU turbidity. The membrane filtration method was used to detect TC and *Escherichia coli* (*E. coli*) simultaneously using modified faecal coliform (mFC) agar prepared according to the manufacturer's specification, while bile esculin agar was used to detect *Enteroccocus* spp. (APHA, 2017).

Percentage removal efficiency for each parameter was calculated using Eq. 1:

$$X = \left(1 - \frac{C_\text{i}}{C_\text{o}}\right) \times 100 \qquad (1)$$

where: X is percentage removal (%); C_o is initial concentration; C_i is final concentration.

Flow rate measurement

To measure the flow rate for the slow sand filter and roughing filter, beakers were placed at the outlets of the respective filters and allowed to collect the effluent for a few minutes. The volume of water collected was measured with a measuring cylinder. The flowrate was obtained in mL/min but was converted to filtration rate by dividing the flowrate by the cross-sectional area of the filter. Filtration rates are all given in m/h.

Determination of head loss

Head loss in the slow sand filtration unit was determined using the Rose (Eq. 2)and Carman-Kozeny (Eq. 3) equations.

$$h = \frac{1.067 C_\text{D} v_s^2 L}{g e^4} \frac{6}{K_\text{S}} \sum \frac{p}{d_\text{g}} \qquad (2)$$

$$h = f' \frac{L}{6} \frac{1-e}{e^3} \frac{V_S^2}{g} \frac{6}{K_\text{S}} \sum \frac{P}{d_\text{g}} \qquad 3)$$

$$\text{where:} \quad C_\text{D} = \frac{24}{Re} \qquad (4)$$

$$\text{Re} = \frac{v_s L}{v} \qquad (5)$$

C_D is coefficient of drag; d is grain size diameter, $d_\text{g} = \sqrt{d_1 \times d_2}$ geometric mean diameter between sieve sizes d_1 and d_2; f is friction factor; g is acceleration due to gravity (9.81 m/s^2); h is head loss (m); K_S is filtration constant 5 based on sieves opening; Re is Reynolds number; P is fraction of sand weight retained on the adjacent sieve; S is shape factor (varies between 6.0 for spherical particle and 8.5 for crushed particles); e is porosity; v is kinematic viscosity (m^2/s); L is depth of filter bed or layer (m); v_s is superficial (approach) filtration velocity (m/s)

RESULTS AND DISCUSSION

Stormwater characteristics before and after sedimentation

The characteristics of the stormwater samples collected after different rainfall events are presented in Table 4. Sedimentation was carried out to reduce turbidity to a level that MSF can treat. The turbidity of the stormwater was in the range of 152–1 983 NTU. After sedimentation, the turbidity of the stormwater reduced to values ranging from 127–592 NTU. The influent for the MSF was the stormwater that had undergone the sedimentation process.

Physical water quality improvement in MSF system

The major criteria used for assessing the physical water quality improvement in the system were effluent turbidity and the degree to

Table 4. Stormwater characteristics and treated effluent values in comparison with various water reuse standards and guidelines

		Parameters							Sources
Reuse purpose		**pH**	**Turbidity (NTU)**	**EC (µS/cm)**	**TDS**	**TC (CFU/100 mL)**	**FC/*E.coli* (CFU/100 mL)**	***Enterococcus* spp. (CFU/100 mL)**	
Drinking		6.5–8.8	≤5	NA	1 000	0	0	0	WHO, 2014
Laundry		6.0–9.0	≤2 ave. 5 max.	NA	2 000^{c}	NA	max. 25^{c}	NA	USEPA, 2012
Recreation		6–9	50	NA	NA	NA	≤400 max.	≤ 70	Health Canada, 2012
Toilet and urinal flushing		6–9	≤2 ave. ≤5 max.	NA	NA	NA	ND ≤200 max.	NA	Health Canada, 2014
Bathing water		6–9	2(g) 1(m)	NA	NA	50(g) 10 000 (m)	100(g) 2 000(m)	NA	Mansilha et al., 2009
Agricultural reuse purpose	Non-food crop		NL^{c}	0.7–3.0^{b,} (dS/m)	450–2 000^{b}		≤200^{a}	max. 800	USEPA, 2012
Agricultural reuse purpose	Food crop		≤2 ave. max. 5						USEPA, 2012
Urban reuse	Restricted access	6.0–9.0	NA	NA	NA	≤200	max. 800	NA	USEPA (2012)
Urban reuse	Unrestricted access	6.0–9.0	≤2	NA	NA	ND	NA	NA	USEPA (2012)
Characteristic of sample stormwater onsite		7.25–8.31	152–1 983	105–230	NA	TNTC	TNTC	TNTC	Present study
Treated effluent from MSF filter		7.1–8.1	5.8–164	NA	NA	360–11 800	0–1 300	120–1 400	Present study

Sources: ^{b}adopted from Ayers and Westcot (1985); ^{c}adopted from Levi Strauss and Co (2014); g – guideline; m – mandatory; NA – not available; ND – no detectable coliform/100 mL, NL – no Limit, TNTC – too numerous to count

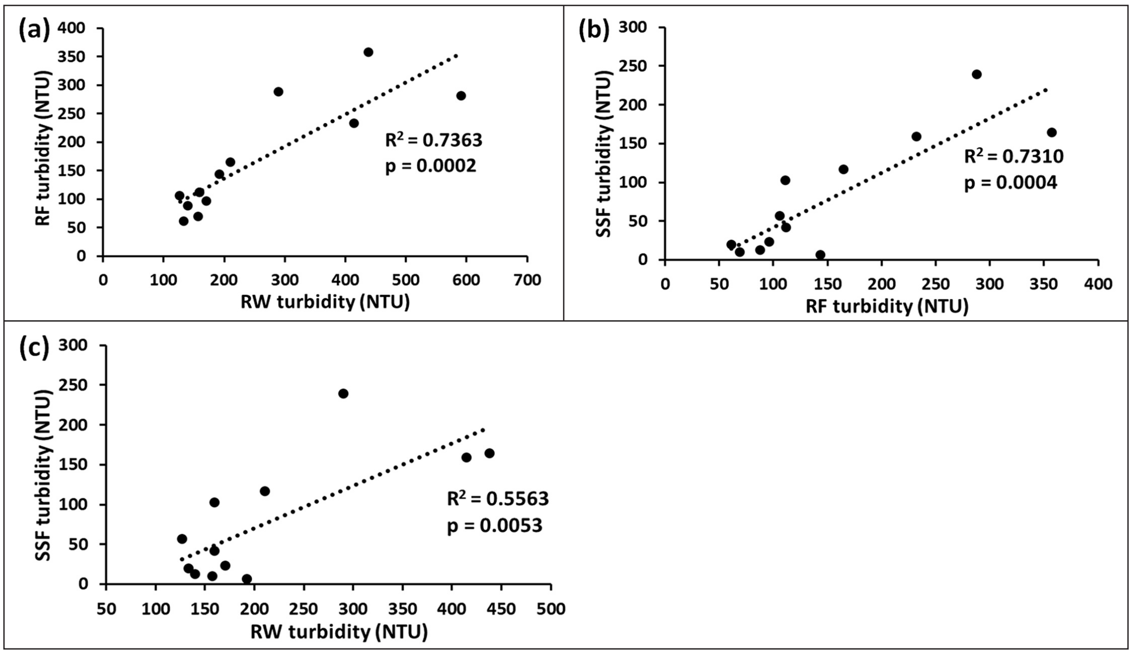


Figure 2. Scatterplot of influent versus effluent for turbidities: (a) raw water (RW) versus roughing filter (RF); (b) roughing filter (RF) versus slow sand filter (SSF); (c) raw water (RW) versus slow sand filter (SSF)

which the turbidity of the untreated water was decreased. Turbidity is believed to be a conveyor of other contaminants like nutrients and pathogens, which can result in biological activity (Vairagi and Dash, 2019). However, the ANOVA results for all the regressions (turbidity versus total coliform, turbidity versus *E. coli*, and turbidity versus *Enterococcus* spp.) were not significant at a 95% confidence level. Alja'fari et al. (2022) reported a similar level of correlation between turbidity and *Enterococcus* in stormwater samples collected from four US cities. In another study, by Bordin et al. (2023), nutrient concentrations, specifically phosphate, nitrate, and nitrite, were found to have no significant correlation with turbidity.

It was observed that, on average, the DRF unit recorded 33% turbidity removal, achieving an average effluent value of 162.38 ± 95.86 NTU, with a range of 61.15–164.05 NTU. The SSF unit attained an average of 58% removal efficiency with an average effluent turbidity value of 73.5 ± 75.9 NTU. Table 4 reveals that the SSF turbidity values from different batches had values ranging from 5.825–164.05 NTU; the lower bound value is slightly above the recommended value but the upper bound value far exceeds the permissible limits for laundry purposes (5 NTU), toilet and urinal flushing (5 NTU), bathing purposes (2 NTU), and agricultural purposes (food crops) (≤2 NTU). The lower limit up to 50 NTU can be used for recreational purposes, but for agricultural purposes (non-crop) and restricted urban reuse purposes, no maximum limit was specified beyond which the effluent is unsuitable for use in this regard.

Figure 2 illustrates the relationship between the influent and effluent turbidities of both individual filter units and the overall system. The regression ANOVA shows a significant correlation across the units and the overall system.

Table 5. Student *t*-test across filter components for turbidity, total coliforms, faecal coliforms and *Enterrococcus* spp.

Parameter	RW vs. SSF		DRF vs. SSF		RW vs. SSF (overall)	
	RW	SSF	DRF	SSF	RW	SSF
Turbidity						
Observations	13	13	13	13	13	13
Mean	245.28	162.38	162.38	73.50	245.2823	73.495
Variance	21 449.53	9 190.295	9 190.30	5 768.22	21 449.53	5 768.224
Deg. of freedom		12		12		12
t statistic		3.695		4.436		4.365
$p(T \geq t)$ one-tail		0.0015		0.0004		0.0005
t critical one-tail		1.782		1.782		1.782
Total coliforms						
Observations	8	8	8	8	8	8
Mean	7 045	5 807.5	5 807.5	4 130	7 045	4 130
Variance	16 316 771	25 387 793	25 387 793	21 825 829	16 316 771	21 825 829
Deg. of freedom		7		7		7
t statistic		1.219		3.202		2.413
$p(T \leq t)$ one-tail		0.132		0.008		0.023
t critical one-tail		1.895		1.895		1.895
Faecal coliforms						
Observations	8	8	8	8	8	8
Mean	661.25	505	505	405	661.25	405
Variance	486 355.357	248 628.571	248 628.571	268 085.714	486 355.357	268 085.714
Deg. of freedom		7		7		7
t statistic		1.063		0.5351		0.8136
$p(T \leq t)$ one-tail		0.1615		0.3046		0.2213
t critical one-tail		1.8946		1.895		1.895
***Enterrococcus* spp.**						
Observations	6	6	6	6	6	6
Mean	4 211.667	2 686.667	2 686.667	648.333	4 211.667	648.333
Variance	16 855 217	11 557 427	11 557 427	203 856.7	16 855 217	203 856.7
Deg. of freedom		5		5		5
t statistic		3.527		1.647		2.322
$p(T \geq t)$ one-tail		0.008		0.0802		0.0339
t critical one-tail		2.015		2.015		2.015

RW – raw water; RF – roughing filter; SSF – slow sand filter

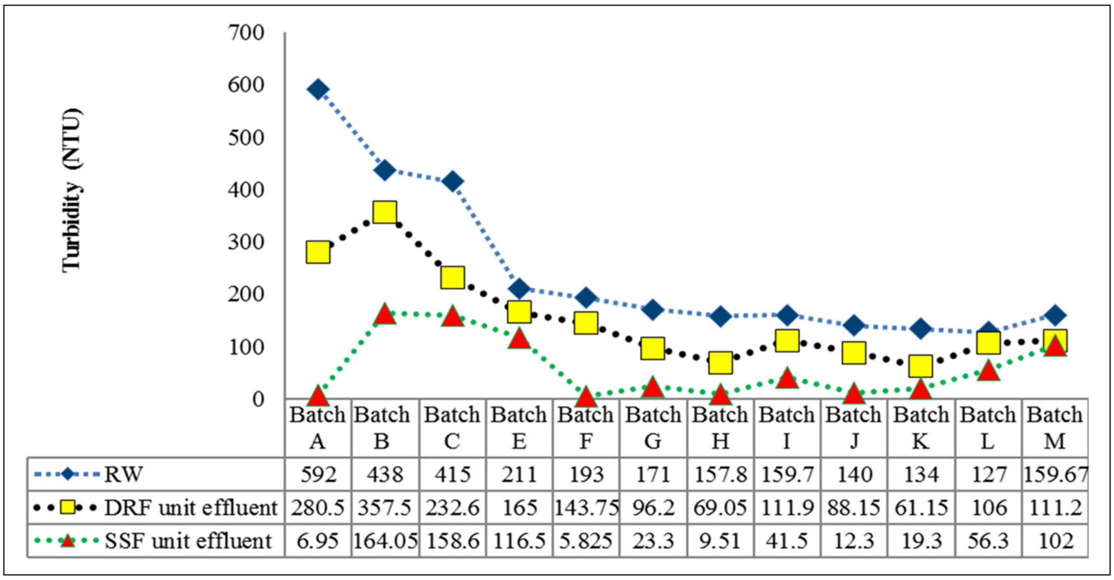
The results of student *t*-tests conducted on all components, constituents, and the complete system are presented in Table 5. Comparing the turbidity of raw water, roughing filter effluent, and slow sand filter effluent, we observe that the turbidity of the raw water was significantly higher than that of the roughing filter effluent, and the turbidity of the roughing filter effluent was significantly higher than that of the slow sand filter effluent. These findings suggest water quality improvement in both the individual filter units and overall efficiency of the filtration process from raw water to slow sand filter.

The effect of filtration rate on turbidity removal efficiency

Figure 3 shows the turbidity removal trend of the DRF unit, SSF unit and MSF unit. It was observed that, to a reasonable extent, each unit accomplished turbidity removal proportional to the raw water turbidity value of the respective batches treated. Interestingly, Batches A, F and H showed a very significant turbidity reduction, to as low as 6.95 NTU, 5.825 NTU and 9.51 NTU, respectively. The turbidity removal efficiency results obtained from the integrated unit, as well as individual units (SSF unit and RF unit) with their respective filtration rates, are shown in Fig. 4. The average turbidity removal efficiency for the DRF obtained in this study was about 33% which is considered reasonable, given that the turbidity of the raw water treated was higher than Wegelin's (1996) recommended value (150 NTU).

The performance of the roughing filter depended on the large fraction of colloidal particles present in the raw water. Losleben (2008) obtained 46% average turbidity removal using a horizontal roughing filter, which is said to be better than a downflow roughing filter. The filtration rate of the RF had a relatively low influence on the performance of the filter (Fig. 4). The RF was operated at filtration rates ranging from 0.01–0.80 m/h. Khan and Farooq (2011) asserted that the turbidity removal efficiency of roughing filters is inversely proportional to the filtration rate, irrespective of the type of water sample, media size or flow direction.

The trendline in Fig. 5 indicates that turbidity values decrease with decreasing filtration rate. However, the rate of change for the RF and SS filtration rates appears to be lower compared to the rate of change of turbidity values. 46% of the effluent can be used for recreational purposes as this satisfies the 50 NTU standard (Table 4).



	Batch A	Batch B	Batch C	Batch E	Batch F	Batch G	Batch H	Batch I	Batch J	Batch K	Batch L	Batch M
RW	592	438	415	211	193	171	157.8	159.7	140	134	127	159.67
DRF unit effluent	280.5	357.5	232.6	165	143.75	96.2	69.05	111.9	88.15	61.15	106	111.2
SSF unit effluent	6.95	164.05	158.6	116.5	5.825	23.3	9.51	41.5	12.3	19.3	56.3	102

Figure 3. Turbidity trend in RF, SSF and MSF

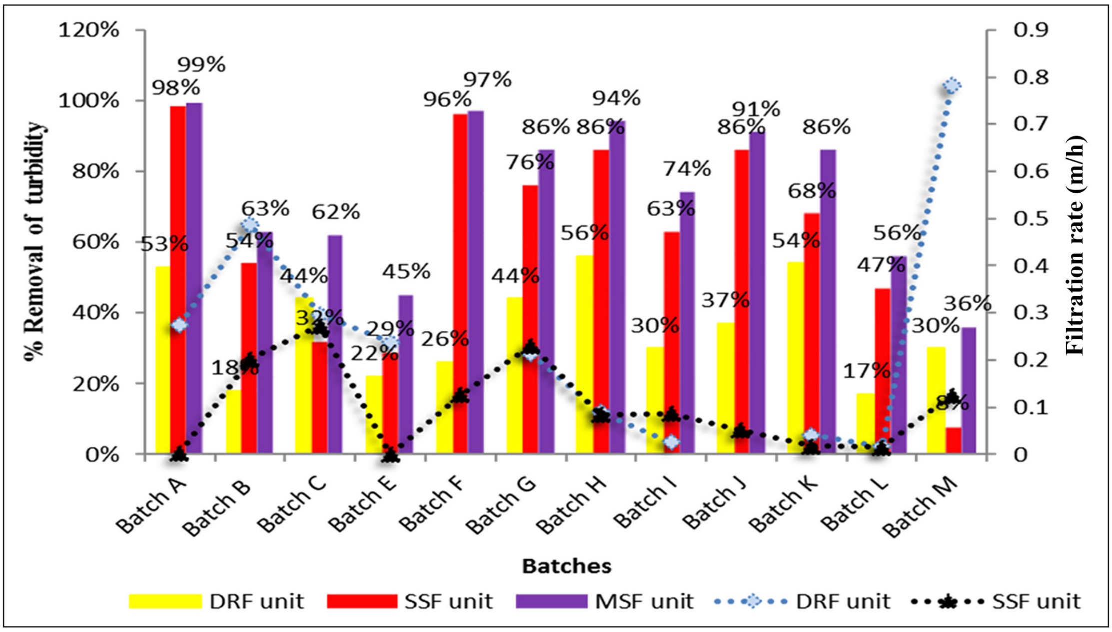


Figure 4. Turbidity removal efficiency versus filtration rate

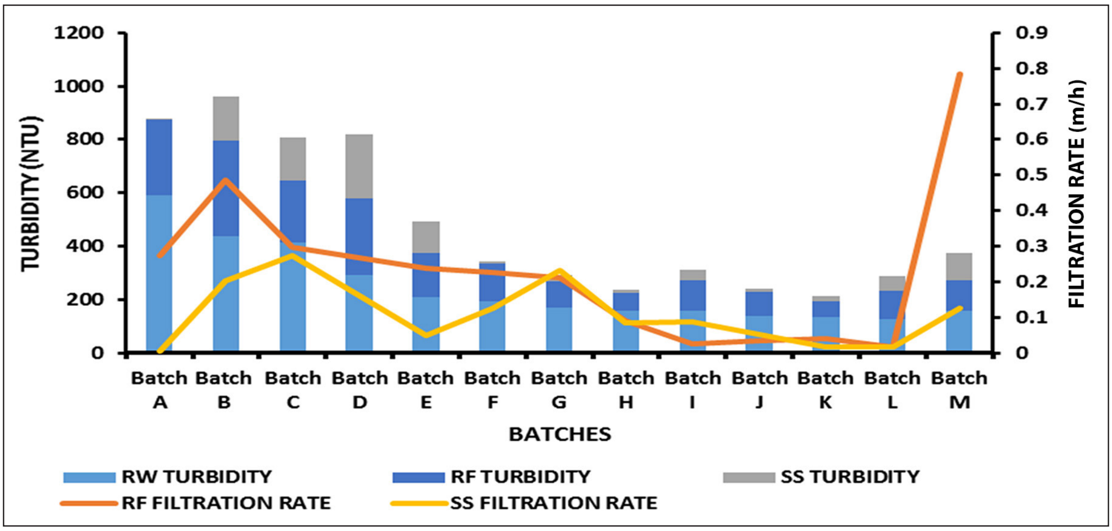


Figure 5. A plot of turbidity against filtration rate

The average turbidity removal for SSF obtained in this study fell within the range of other authors' observations, i.e. generally within 50–90% (Ahammed and Davra, 2011; Elbana et al., 2012; Coral et al., 2014). From Figs 4 and 5 it can be observed that the slow sand filter turbidity removal efficiency is influenced by the filtration rate. The slow sand filter was operated at filtration rates of 0.004–0.280 m/h, which contributed significantly to the high efficiencies obtained. This finding is in agreement with Mohammed et al. (1996), who asserted that turbidity removal efficiency decreases significantly with increasing filtration rates. The best removal efficiency was obtained in Batch A at the lowest filtration rate (0.00419 m/h). However, as the filtration rate increased the turbidity removal efficiency declined from Batch B to Batch D. Another significant influence on the performance of the filter is the turbidity value of the initial raw water, which was above the Wegelin (1996) recommended value (150 NTU).

Moreso, the results of the regression ANOVA between filtration rate and effluent turbidity (Fig. 6) indicate that, even though only about 50% of the variability in effluent turbidity can be accounted for by filtration rate, there is a significant relationship between the two variables ($p = 0.007$).

The trendline in Fig. 7 is a two-point moving average between effluent turbidity and the cumulative volume of water treated. The plot reveals that at the start of the experiment, effluent turbidity increased and then gradually decreased before rising again. Filters are generally observed to follow a pattern where performance starts poorly, improves over time and maturation, and then eventually deteriorates again when preferential flow and/or clogging become an issue (Maiyo et al., 2023).

Generally, it was observed that performance did not follow a steadily increasing trend (Fig. 5) because each batch was run intermittently (flow was not continuous). Young-Rojanchi and Madramooto (2014) revealed that continuously operated rather than intermittently operated mode produces better results. Besides, the use of the varying value of raw water turbidity at varying filtration rates might also have influenced the quality of the effluents from the roughing filter and slow sand filter, therefore causing the effluent to have varying values of turbidity. In conclusion, the MSF unit achieved an average of 70% (73.5 NTU) removal efficiency which compares well to other researchers' work.

Microbial water quality improvement in MSF system

Bacteriological water quality is a crucial parameter that must be thoroughly considered in water treatment. WHO recommends zero tolerance for disease-causing microorganisms, no matter how clear and pleasant the water may appear. Slow sand filtration is one of the most efficient processes for the production of hygienically safe drinking water. Roughing filtration provides the requisite protection for slow sand filtration in adverse raw-water physical conditions. It also contributes significantly to improving microbiological quality. Table 4 gives the total coliform (TC) of the treated effluent as ranging from 360–11 800 CFU/100 mL; the lower limit values up until 2 000 CFU/mL fall within the permissible limit for recreational water reuse. The FC/*E. coli* of the treated stormwater gave values ranging from 0–1 300 CFU/100 mL. The lower limit values fall within the maximum permissible limit for recreation, toilet and urinal flushing, agricultural purposes and restricted urban , but beyond these values (Table 4) the water becomes unsuitable for reuse. However, the FC values obtained satisfy the bathing water purpose (do not exceed 2 000 CFU/100 mL). *Enterococcus* spp. in the treated effluent ranged from 120–1 400 CFU/100 mL, and exceeded the recommended values for

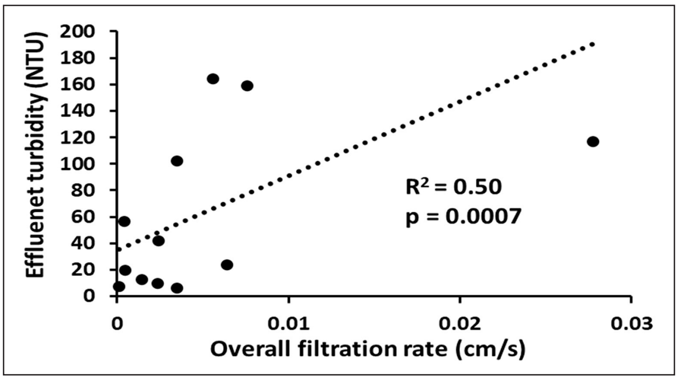


Figure 6. Scatter plot of filtration rate versus effluent turbidity

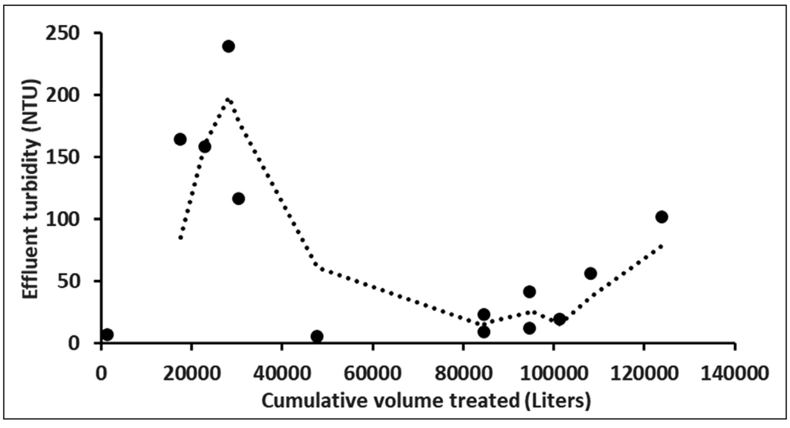


Figure 7. A plot of effluent concentration versus total treated flow

recreational water. Low-cost disinfection can, however, make water suitable for almost all reuse purposes.

The percentage removal efficiencies for TC, FC and *Enterococcus* spp. at their respective filtration rates are presented in Fig. 8.

The average microbial counts and average removal efficiencies for microbial parameters by DRF unit, SSF units and the entire MSF are presented in Table 6. The highest removal efficiencies were recorded for Batch L. The SSF removal efficiency was low compared to the average values documented in the literature. This might have been because the biological layer was not allowed to form, as the water head was not allowed to build up in the SSF unit. Nabwayo (2016) observed that removal efficiency for both TC and FC was as low as 20–57% before 26 days (considered as the maturation period). However, after 26 days, a significant increase of 75–100% removal efficiency was experienced for the SSF filter.

*The effect of filtration rate and initial microbial load on removal efficiency of total coliform, faecal coliform (***E. coli***) and* **Enterococcus** *spp.*

The highest removal efficiency for the respective microbes was attained at the lowest filtration rate (Batch L) (Fig. 8). It was also observed that removal efficiency was not only influenced by filtration rate; initial microbial load of the raw water also had a significant influence. Batch B and Batch L had the highest removal efficiencies, while Batch I had the lowest. In addition, the highest removal efficiency was achieved for FC with the lowest microbial load (Batches K, L and M). This notwithstanding, the values obtained indicate that although the MSF (74%, 90% and 86% overall removal efficiency for TC, FC and *Enterococcus* spp., respectively) proved efficient with regards to improving the bacteriological water quality, terminal disinfection (chlorine or solar) is required to further treat the effluent and safeguard the system against microorganism breakthroughs. However, the dosage of chemicals needed is then expected to be lower than required without pre-treatment with MSF. The slow filtration rates in SSF, of 0.004–0.280 m/h, also contributed significantly to the high efficiencies. A low filtration rate causes water to be within the filter bed for a longer retention time and hence leads to improved removal efficiency (Nabwayo, 2016).

The microbial removal rate decreases as the RF filtration rate increases with an increasing SS filtration rate (Fig. 8); 62.5% of the effluent satisfies the FC standard (Table 4) for toilet and urinal and agricultural use (non-food crop), while 87.5% of the effluent meets the standard for urban reuse (restricted access). 66.67% of

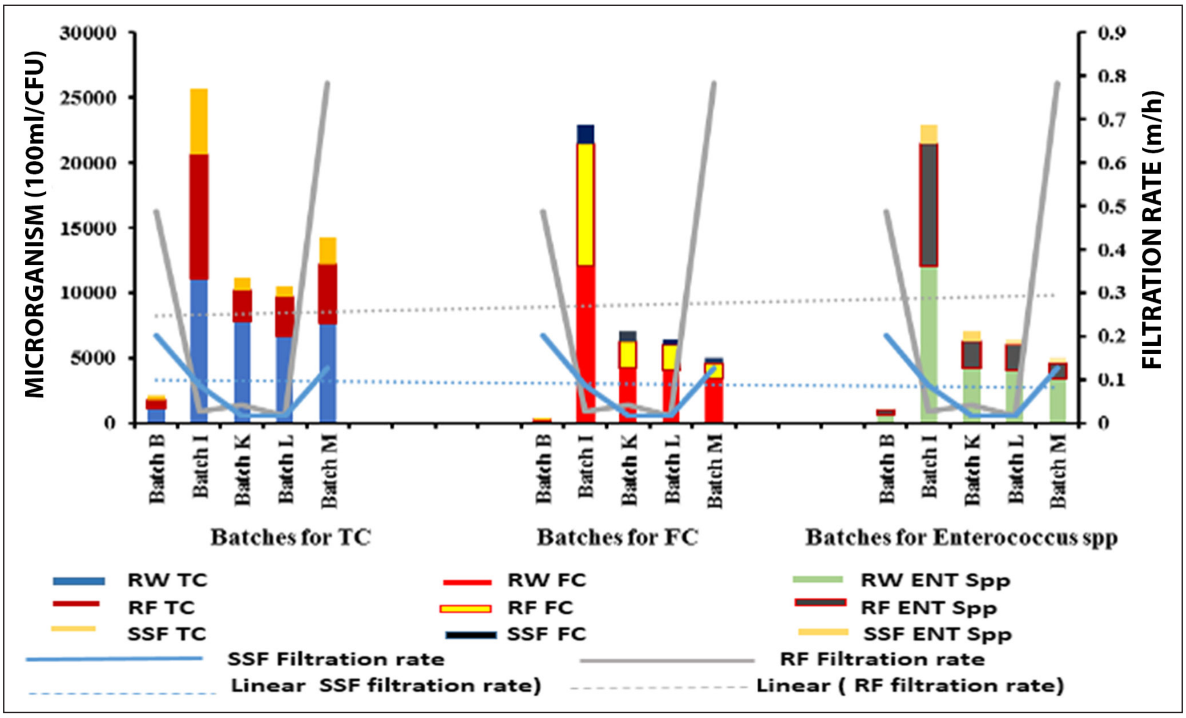


Figure 8. A plot of microorganism load (TC, *E. coli*, *Enterococcus* spp.) against filtration rate

Table 6. Performance of MSF in improving microbial water quality

Performance	Microbial parameters	DRF unit	SSF unit	MSF unit
Average microbial concentration (CFU/100 mL)	TC	5 807.5 ± 5 038.6	4 130 ± 4 671.8	4 130 ± 4 671.8
	FC	505 ± 498.63	405 ± 517.8	405 ± 517.8
	Enterococcus spp.	505 ± 498.63	648.33 ± 451.5	648.33 ± 451.5
Best removal efficiency (%)	TC		73 (Batch L)	88
	FC		100 (Batches L, K and M)	100
	Enterococcus spp.		85 (Batch I)	90. (Batch L)
Average removal efficiency (%)	TC	45	56	74
	FC	43	86	90
	Enterococcus spp.	44	76	86

the effluent satisfies the *Enterococcus* spp. standard for agricultural reuse (non-food crop). The entire sample satisfies the TC bathing standard (Table 4).

Physicochemical water quality improvement in a multi-stage filtration system

During the experimental run, it was noticed that the temperature of the raw water varied from 27.6–29.4°C, which should encourage bacteriological growth in water. The pH values varied from 7.1–8.1, which is within the guideline values (6.0–9.0) for laundry, bathing, toilet flushing, urban reuse and agricultural purposes. There is a strong correlation between EC and TDS (Fig. 9) – the lines for EC and TDS share some common points. It was also observed that there was a slight increase in the values of EC and TDS with filtration stage. This may be due to the biochemical reaction in the filter media that initiates ionization of organic compounds thereby increasing total dissolved ions. Some portion of these ions adsorbed on the filter media escaped with the effluent resulting in a total increase of EC and TDS in the later part of the experimental run (Rahman, 2010). The average EC values for the effluents from the SSF are 152 µS/cm, with values ranging from 100–190 µS/cm, and 106 mg/L for TDS with values ranging from 70–130 mg/L. All values obtained fell within all the water reuse guidelines considered in this study (Table 4).

Head loss in the slow sand filter

Using the Rose and Carman-Kozeny equations the head loss for the slow sand filter was calculated and compared (Table 7). The sieve analysis result was used in computing the result: 0.4 was used for porosity (e) based on the common values used in literature and 0.75 was used as the shape factor (K_S) – this is the average shape factor value for various types of sand.

The head loss in the slow sand filter was very low because the flow condition was very low and the system was operated intermittently. Therefore, there was no growth of the biological layer. To remove colloidal particles that cause turbidity in water, size exclusion is utilized, which leads to the deposition of particles within the sand matrix. This deposition and subsequent decay of the organic matter it contains predominantly occur at the top of the sand bed, resulting in the formation of a biologically active surface layer called Schmutzdecke (Guchi, 2015; Lubarsky et al., 2022). As the deposition and Schmutzdecke accumulate, it progressively reduces the pore size of the filter, leading to an increase in head loss and a decrease in flow rate (Boller and Kavanaugh, 1995).

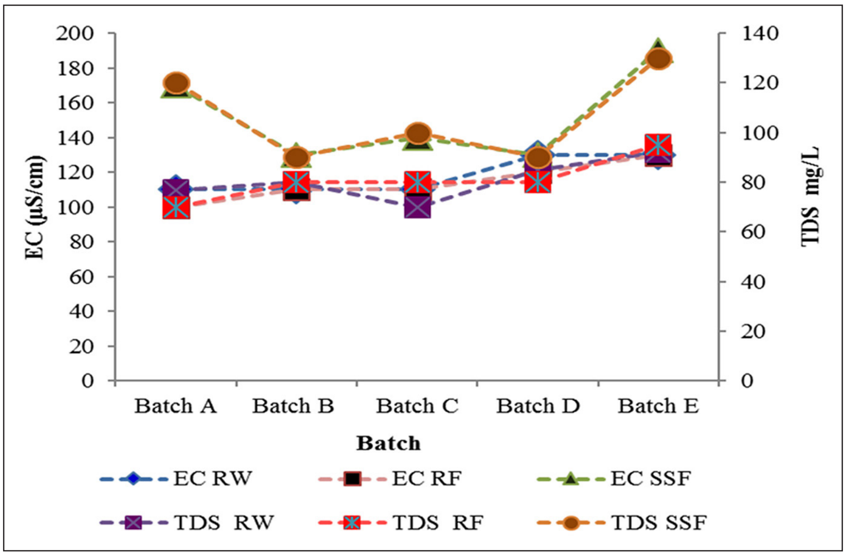


Figure 9. EC and TDS in RF, SS and MSF

Table 7. Computed head loss at various filtration rates

Batches	Filtration rate, *V* (cm/s)	Reynolds number (Re)	CD = 24/Re	f’	Head loss (cm) (Rose equation)	Head loss (cm) (Carman-Kozeny equation)
Batch A	0.000116	0.000424	56 617	773 487.75	0.6833	0.3500
Batch B	0.005626	0.020497	1 170	15 997.75	33.0142	16.92271
Batch C	0.007581	0.027619	868	11 872.75	44.4714	22.80388
Batch D	0.02777	0.101169	237	3 241.75	162.9237	83.54332
Batch E	0.02777	0.101169	237	3 241.75	162.9237	83.54332
Batch F	0.003527	0.012848	1 867	25 519.75	20.7008	10.60757
Batch G	0.006412	0.02336	1 027	14 036.75	37.6404	19.2862
Batch H	0.002359	0.008594	2 792	38 151.75	13.8509	7.095344
Batch I	0.002429	0.00885	2 711	37 048.75	14.2620	7.306734
Batch J	0.001449	0.005277	4 547	62 131.75	8.5052	4.356833
Batch K	0.000486	0.00177	13 555	185 195.75	2.8537	1.461636
Batch L	0.00044	0.001604	14 967	204 474.75	2.5848	1.323825
Batch M	0.003493	0.012727	1 885	25 763.75	20.5073	10.50758

CONCLUSION

The overall performance of the MSF was laudable, as it resulted in considerably improved stormwater quality, despite the turbidity value of the stormwater treated being significantly above the recommended value given in the literature. The entire MSF unit achieved an average overall turbidity removal efficiency of 70%. It is also noteworthy that the highest removal efficiency achieved (98% for SSF and 99% for MSF) was at the lowest filtration rate (0.00419 m/h). The downflow RF unit recorded an average of 33% turbidity removal, achieving an average effluent value of 162.38 NTU The SSF unit attained an average of 58% removal with an average effluent turbidity of 73.5 NTU. The treated effluent is suitable for agricultural (non-crop) and restricted urban reuse purposes.

On average, the downflow RF unit registered 45% (4 018 CFU/100 mL) total coliforms, 43% (2 978 CFU/100 mL) faecal coliforms and 44% (3 700 CFU/100 mL) *Enterococcus* spp. removal efficiency. The SSF units recorded 56% (1 872 CFU/100 mL) total coliforms, 86% (584 CFU/100 mL) faecal coliforms and 76% (725 CFU/100 mL) *Enterococcus* spp. removal. The entire MSF unit recorded an overall removal efficiency of 74% (1 872 CFU/100 mL), 90% (584 CFU/100 mL) and 86% (725 CFU/100 mL) for total coliforms, faecal coliforms and *Enterococcus* spp., respectively. Low-cost disinfection is needed to achieve the recommended standards for almost all reuse purposes.

The pH (7.1–8.1), temperature (27.6–29.4°C), EC (100–190 µs/cm) and TDS (70–130 mg/L) of the treated stormwater were all within recommended guidelines for all reuse purposes considered.

In conclusion, since the MSF treatment method may not require much capital, sophisticated processes run by skilled manpower, it can be employed in a rural area in, for example, Nigeria, that lacks access to sufficient clean water, consequently taking care of domestic water demands other than drinking water.

AUTHOR CONTRIBUTIONS

CVC – methodology of the study, data collection and fieldwork, sample/data analysis, interpretation of results, writing of the initial draft; CCN – conceptualization and methodology of the study, sample/data analysis, interpretation of results, writing of the initial draft; CNN – writing of the initial draft; EJN – sample/data analysis, interpretation of results, writing of the initial draft.

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