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ORIGINAL RESEARCH

Optimal bed thickness and effective size for improving wastewater quality for irrigation

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Abstract

With the increased use of wastewater for irrigation, there is the need to reduce the contaminant levels in wastewater. The slow sand filtration (SSF) is one such method that can be used to improve wastewater quality. However, the treatment quality depends among other factors on the depth of sand bed and the effective size. Acquiring sand of a particular effective size is becoming increasing difficulty and, therefore, this study sought to investigate over a specified area, the optimal depth and effective size that will be able to get rid of contaminants in wastewater. In separate experiments, three depths (30 cm, 40 cm and 50 cm) and two effective sizes (0.27 mm and 0.45 mm) were set up to investigate their effectiveness in removing Faecal coliform, *E. coli* and heavy metals (Pb, Cu and Fe) for wastewater from a peri-urban drain used for irrigating vegetables. Results showed that a minimum sand bed thickness of 40 cm and an effective size of up to 0.45 mm reduced the contaminants tested significantly, wastewater from the drain can be treated. It must be mentioned that the finer sand (0.27 mm) had a slightly better removal efficiency. This implies that the extra cost of acquiring sand of relatively smaller effective size and a higher bed depth with the aim of improving wastewater quality can be saved. Further investigations are being carried out on the combined effects of the optimal sand bed depth and effective size.

Keywords Bed depth · Effective size · Kawukudi · Slow sand filter · Wastewater irrigation

Introduction

Water, the most common liquid on earth covering about three-quarters of the earth's surface is essential for the survival of all living things. Despite its valuableness to life, it is increasingly becoming a scarce resource in many arid and semi-arid countries [1]. It is used by humans in many ways such as drinking, domestic use, industrial use and agricultural irrigation. Agriculture is the largest consumer of the earth's fresh water of about 42% [2].

Wastewater is any water used either domestically or industrially and contains waste materials or substances. It was defined by Raschid-Sally and Jayakody [3] as a combination of domestic effluents (consisting of black and grey water), effluents from commercial establishments (like hospitals), industrial effluents (where present) and stormwater from runoff. The composition of wastewater is dependent on the uses to which the water was put and may contain a variety of pathogens and other contaminants such as bacteria, viruses, protozoa, helminth's eggs, heavy metals, organic and inorganic chemicals [4–7].

The rapid growth in the world's population, industrialisation, urbanisation and changing lifestyle are some major factors that result in increased volume of waste generation, pressure on limited water resources and increased wastewater production [8–10]. As competition for freshwater increases in urban and semi-urban centres, irrigated agriculture tends to suffer significantly as irrigation has been the largest consumer of water [2, 11]. As a result, many countries (mostly in arid and semi-arid regions) have turned to alternative water sources (with the potential of supporting agricultural use) to supplement the limited freshwater sources and, to raise both agricultural productivity and life standards of the rural poor [12]. In Pakistan, it was reported that 80% of farmers use untreated wastewater for irrigation [1].

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The story is not too different in Ghana as small farms in urban and peri-urban areas of Accra use wastewater from drains to irrigate crops. It was reported that 70% of farmers in Kumasi use polluted streams for irrigation [13]. Qadir et al. [14] reported that the increasing use of wastewater for irrigation is basically as a result of the scarcity of water, increase in the cost of fertilisers and the fear of food shortage crisis hitting the world. According to the World Health Organization, more than 10% of the world's population consumes wastewater-irrigated food products [15]. This practice has some benefits and several other implications as far as soil properties and human health is concerned [13, 16].

Vegetables irrigated with wastewater have been found to contain residues as Lead, Copper, Mercury, Iron, Zinc, Nickel, Cobalt and Arsenic which causes carcinogenesis, cell damage and loss of cellular functions [1, 13, 17–19]. Therefore, low technology, relatively low-cost treatment, with ease of operation and minimal maintenance options are being considered to improve the quality of wastewater.

One such method of wastewater treatment is the slow sand filter method (SSF) [16]. The SSF is a simple wastewater treatment technology that can be used to reduce the pollutant load of wastewater. It has been in use for centuries for the treatment of water for domestic use [20, 21]. Slow sand filtration involves allowing water to slowly pass through a bed of sand or other porous material for treatment. It involves the use of both physical and biological pathogen control mechanisms [20, 22, 23].

It has over the years been considered as probably the simplest, effective and low-cost water treatment process used in many developing countries [24]. It requires few technical components for construction, natural materials for the filtrate and has no chemicals added. It is being used in wastewater treatment in many developing countries for irrigation purposes mainly because of its efficient performance in the removal of pathogens and chemicals in wastewater when used [25].

The SSF comprises of the supernatant water (provides the hydraulic pressure that pushes water through the sand filter below), biofilm layer (called Schmutzdecke, serves as the main source of biological pathogen control in the sand filter [26]), bed of graded sand (which provides a medium for physical filtration to occur and microorganisms to grow) on layers of gravels (allows for free drainage of water from the sand bed to the outlet and also prevents sand from clogging the outlet pipes or sand from leaving the filter tank [27]. The filter media is enclosed with openings at both ends allowing water to flow in and out (under gravity). The filtration process—a form of natural, biological water treatment—is used in the removal of solids, precipitates, turbidity (muddiness) and in some cases, bacterial particles that produce bad taste and odour [28].

In the design of the SSF, certain design parameters/characteristics (such as depth of sand bed, effective size, uniformity coefficient, hydraulic retention time and hydraulic loading rate of the filter media) are crucial for the effective performance of the filter. Barrett et al. [27] wrote on the design of the SSF and reported that the major component of the filter is the sand bed through which the water flows. Work has been done by a few researchers on filter design characteristics of SSF for improving wastewater quality for irrigation yielded good results and are summarised in Table 1 [23, 29–32].

From Table 1, it can be seen that SSFs in both experimental and field work have been designed with a depth of up to 1.2 m and effective size of up to 0.45. It is probable that bed depth significantly improves treatment quality; however, it is quite expensive to procure even for experimental work and even more challenging for a particular effective size. Since these parameters together influence retention time, it is prudent to optimise bed depth and effective size over a specified area that will effectively treat wastewater for irrigation [30].

The reported finding agrees to the set objectives of the work in the sense that the results reveal the suitability and effectiveness of the slow sand bed in the removal of suspended particles in wastewater as well as reducing pH, electrical conductivity and biological contaminant, *E coli*. [23, 32, 37]. However, the above-mentioned studies did not emphasise the role of uniformity coefficient, hydraulic retention time and hydraulic loading rate which are influenced by effective sizes and the depth of the sand bed to improve the wastewater quality to be used for irrigation purposes. In addition, most studies did not consider the removal of heavy metals.

Our work situates in this context and seeks to optimise over a specified area the depth of sand bed that would significantly improve wastewater quality for irrigation. It also seeks to investigate over a specified area and depth, the effect of varying effective size (d_{10}) in improving the physico-chemical as well as biological quality of wastewater for irrigation.

Depth of filter media

Though Barrett et al. [27] reported that the contaminant removal efficiency of the sand bed depends more upon the maturity of the "*Schmutzdecke*" than upon its depth, other researchers have affirmed that the depth of the sand media through which water passes is crucial to the water treatment efficiency [23, 24, 36, 38]. The biological activity of the "*Schmutzdecke*" is enhanced as the bed thickness increases. The microorganisms and other suspended particles in the wastewater travel through the depth of the sand media to ensure a higher removal efficiency of contaminants at higher sand depths.

Table 1 SSF design parameters. Modified after Pyper and Logsdon [33]

Design criteria	Bed depth (m)	Effective size (mm)	Filtration rate ($m^3/h/m^2$)	Supported bed (m)	Supernatant water (m)	Retention time	Scale of work	Parameters tested	Removal efficiency (%)
Ten States Standards USA [61]	0.8	0.3–0.45	0.08–0.24	0.4–0.6	0.9	–	Field	–	–
Huisman and Wood [30]	1.2	0.15–0.35	0.1–0.4	Not reported	1–1.5	–	Experimental	–	–
Visscher et al. [62]	0.9	0.15–0.30	0.1–0.2	0.3–0.5	1	–	Field		
Bagundol et al. [23]	0.3–0.9	0.16–0.30	0.2–0.4	0.1–0.3	Not reported	Not reported	Experimental	*E. coli*	95.4
								Turbidity	99.6
Thomas and Kani [32]	–	0.3–3.0	1.38×10^{-3}	Not reported	Not reported	12 m 21 s	Experimental	Turbidity	86
								pH	13.3
								Electrical conductivity	77
Muhammad et al. [24]	0.73	0.20	0.1	0.06	1.4	Not reported	Experimental	Faecal coliform	99.6
		0.35						Turbidity	96.5
								Colour	95.1
	0.40	0.45						Faecal coliform	98.4
								Turbidity	87.5
								colour	72
Troyan and Hansen [34]	1.07	0.25–0.35	0.2	–	–	–	–	Viruses	99.8
								Coliform	99
								Turbidity	40
Poynter and Slade [35]	0.60		0.2					Polio virus 1	99.99
Van Dijk and Oomen [36]	0.6–1.4	0.15–0.35	0.1–0.2	0.4–0.7	1–1.5	–	Field	Pathogenic bacterial	99–99.9

Muhammad et al. [24] confirmed that most of the bacteriological purification of wastewater occurs within the top 400 mm of sand bed. Increasing sand bed depth causes increases in the total surface area of the sand grains and ultimately the total adsorption capacity throughout the depth of the sand bed in the treatment of wastewater by the SSF. This enhances mechanical entrapment of smaller particles, including viruses, colloidal matter, pathogenic bacteria, *E. coli*, turbidity and colour removal efficiencies. This happens when the bacteria become entrapped in the spaces between the sand grains or become attached to each other or the bacteria may die due to scarcity of food and oxygen depletion [23, 34–36, 39].

Effective size (D_{10})

Effective size (D_{10}) is the “diameter in the particle-size distribution curve corresponding to 10% finer” [40]. In SSF, the smaller effective sizes of the filter media produce good quality effluent [30, 31]. This is confirmed by Van Der Hoek et al. [41] who explored the performance of two grain sizes with effective sizes 0.19 mm and 0.25 mm, and Rolland et al. [42] also reported that the biological removal potential of sand media with effective sizes of 0.33 mm and 0.8 mm produced a good effluent quality.

Results from experiment conducted by Muhammad et al. [24] to measure the significance of increasing effective sizes from 0.20 to 0.35 mm to 0.45 mm on the performance of slow sand filter showed good effluent quality with the smaller effective size giving slightly better results. Langenbach [43] agreed with the conclusion of Muhammad et al. [24] after his experiments showed no significant effluent quality for effective sizes in the range of 0.25–0.80 mm. It is clear from the studies that media with smaller effective size are finer and can better trap particles in the wastewater thereby, resulting in better effluent quality.

It must be reiterated that effective size influences uniformity coefficient, hydraulic retention time as well as infiltration rate. These are further discussed below.

Uniformity coefficient (C_u)

The C_u tells the homogeneity of the grain size distribution. It is calculated by finding the ratio of 60% finer and 10% finer [40]. The uniformity coefficient plays a vital role in the removal of pollutants and prevents clogging. Huisman and Wood [30] recommended that the sand media should be fairly uniform with C_u between 1 and 3. Studies conducted on the influence of uniformity coefficient (C_u) on effluent quality considering the removal efficiency of colour, turbidity, heavy metal removal (total iron and manganese), faecal coliform and heterotrophic bacteria colonies confirmed that uniformity coefficient (C_u) higher than the World Health Organization (WHO)'s recommendation would lead to a lower filter run time [43, 44].

Hydraulic retention time (HRT)/residence time

The hydraulic retention time (HRT) is also referred to as the hydraulic residence time and describes how long it takes raw water to travel through sand media during filtration, and it is defined as the measure of how much water is moving through the filter over a certain amount of time. The retention time is weighted by the volume of water stored within the filter [45]. In other words, it is the theoretical time the wastewater will take to journey through the entire depth of the filter media.

Mathematically,

$$HRT = \frac{V}{Q}, \tag{1}$$

where

V is volume of filter tank (m^3)

Q is the flow rate of influent (m^3/s).

An important aspect of the SSF is the quality of the filtrate and the hydraulic retention time (HRT) of the water within the filter media. The type of sand (coarse or fine), how long filter is use bed depth and effective size are important factors that directly affects the retention time [46–48]. The filter sand needs to be fine enough to provide sufficient filtration of suspended materials of concern. Long HRT ensures significant contact of organic materials, biofilm formation increase the degree of water treatment. The hydraulic retention time of most SSF systems ranges from 5 to 6 h [49].

Studies have shown that increasing the bed thickness increases the hydraulic retention time and the infiltration rate resulting in higher degree of the treated water. Missimer et al. [49] listed the hydraulic retention time from a set of slow sand filters with differing bed thicknesses and infiltration rate as seen in Table 2.

From Table 2, it is clear that bed thickness and infiltration time are major factors that affect the quality of water treated. Thus, increased hydraulic retention time tends to increase the degree of water treated. From the discussions, so far considering bed thickness and effective size, we can see that there is cost involved in attaining better effluent quality results with respect to the design of SSF that is why this study seeks to optimise bed thickness as well as the effective size that can still clean pathogens as well heavy metals from wastewater.

Materials and methods

This research was carried out in two stages: design and construction of the slow sand bed filter which involved the selection of sand, gravels and stones, sieve analysis, and the design and set up of the SSF. The water quality analysis involved obtaining the water sample and testing for the microbiological and heavy metal parameters. The study site and the statistical method used in analysing the results are further discussed.

Study site description

The study site, Kawukudi, is a developing area in the Accra Metropolis located in the Greater Accra Region of Ghana. It is located south of Ghana to the Gulf of Guinea (5° 35′ 43″

Table 2 Hydraulic retention time as a function of infiltration rate and bed thickness [49]

Infiltration rate (m/h)	Infiltration rate (m/d)	Bed thickness (m)	Hydraulic retention time (h)
0.05	1.2	0.9	18
0.1	2.4	1.0	10
0.2	4.8	1.25	6.25
0.3	7.2	1.3	4.3
0.4	9.6	1.4	3.5
0.5	12.0	1.5	3.0

North, 0° 11′ 21″ East). The site, a peri-urban environment was chosen due to the presence of small-scale vegetable farms. The primary and main source of water used in the irrigation of these farms is the wastewater from the drain that passes the area. The wastewater in this drain comes from domestic and industrial sources.

Materials and experimental setups

The research was conducted in two experimental setups and the aforementioned two stages were undertaken for each setup. The experimental setups were done at the premises of the Agricultural Engineering Workshop of the University of Ghana. The first setup consists of a 250-L drum, diffuser bowl, Polyvinyl Chloride (PVC) pipe outlet, tap, fine and coarse aggregates (with boulders ranging between 13.4 and 18.9 mm and gravels, 2.37–5.48 mm in diameter). The dimensions of the drum were 915-mm tall, 540 mm in diameter and can hold a total volume of 0.21 m^3 of water.

The second setup was made up of three 1000-L tanks of equal area, Polyvinyl Chloride (PVC) pipe outlet, tap, fine and coarse aggregates. The dimensions of the tank were 109 mm by 94 mm in area with a height of 97 mm and can hold a total volume of 1.02 m^3 of water. The grain aggregates ranged from boulders of 60 mm in diameter (at the base) to fine sand of different effective sizes. The coarse aggregates (consisting of the boulders and gravels) were obtained from a construction site. The boulders form the underdrain of the SSF with the gravels on top of it. The fine aggregate (sand), obtained from the beach was poured on the gravels to form the fine media, a very important part of the SSF setup.

Sand, gravels and boulders

The choice of sand, gravels and boulders affects the removal performance of pollutants and purification efficiency of the filter [50]. The coarse sand or gravel layers which support the sand media layer must be of adequate grain size to prevent migration of the sand through them. Larger grain sizes allow for faster movement of wastewater through the sand media and the more wastewater can be filtered [46].

For an SSF, an adequate grain size of the filtration media should be between 0.15 and 0.35 mm [30]. However, studies by Muhammad et al. [24] and Anggraini [51] revealed that sand with effective size up to 0.45 mm can produce good effluent quality. Thus, the sand media was sorted and measured using a stack of mechanical sieves to obtain effective sizes in the range of 0.15–0.45 mm.

Grain size distribution of sand

This test was performed to determine the distribution (percentage of different grain sizes) of large sized particles and fine particles of the sand. The distribution of the different grain sizes affects the rate of infiltration of the influent in the sand media as well as the hydraulic loading rates of the system. The method used is the ASTM D 422—Standard Test Method for Particle-Size Analysis of Soils. The equipment used were a mass balance, set of clean sieves, mechanical sieve shaker and a cleaning brush.

Investigating filter bed thickness

This setup (Fig. 1) was designed using the 250-L plastic drum. A hole was created at the base of the drum using a

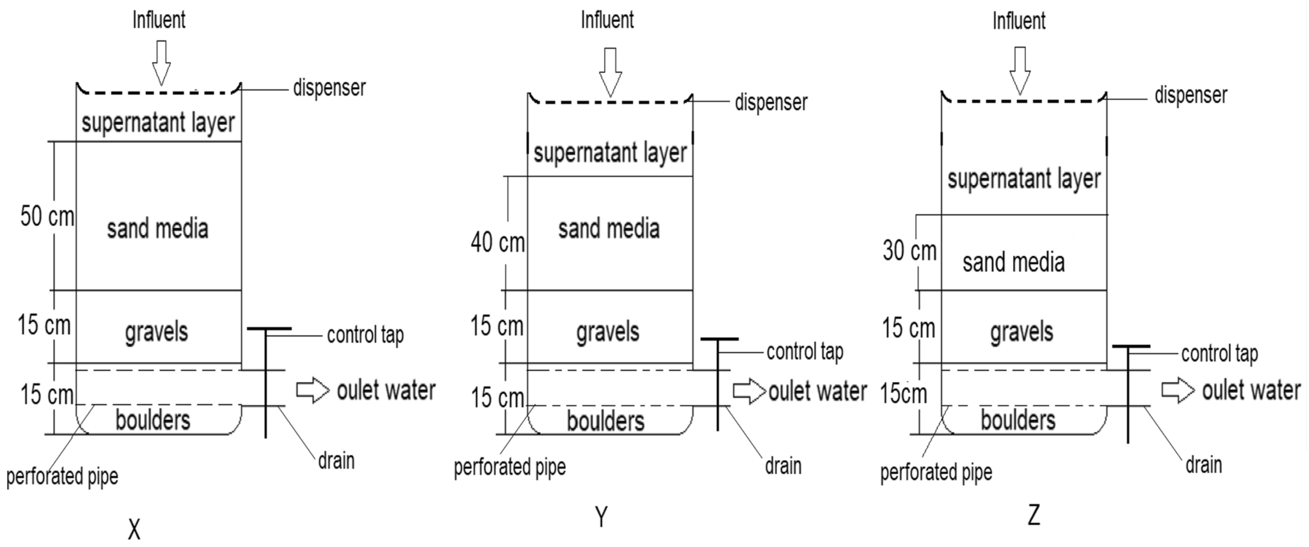

Fig. 1 The slow sand filter arrangement

hand drill, and the edges filed to the required diameter. A white thread socket was fitted into the hole created at the base. The socket was connected to a T-Pipe which also connects to 2 other T-Pipes and elbows at the base of the water drum as shown in (Fig. 2). Care was taken to allow for easy removal of the water from the drum and for easy regulation of the filtrate flow rate. The diffuser bowl, wide enough to cover the top surface of the drum was placed on the opened top of the drum to serve as inlet control.

The washed gravels were used as the support of the sand media. Stones with sizes between 13.4 and 18.9 mm (serving as the boulders) were placed at the bottom of the drum to a depth of 15 cm. Right on top of it was placed another batch of gravels with sizes between 2.37 and 5.48 mm to a depth of 15 cm. This gravel support holds the sand media in place to prevent loss of the sand grains and choking of the outlet pipes.

Elbows and Tees connecting the pipes at the base to outlets

Completed Design

Fig. 2 Arrangement of pipes in the tank

Boulders with diameters between 13.4 mm - 18.9 mm at the base of the drum (15 cm depth)

Gravels with diameters between 2.37 mm - 5.48 mm on boulder layer (15 cm depth)

Coarse and Fine sand of effective size 0.26 mm on the Boulder - Gravel layer (30 cm depth)

Fig. 3 Arrangement of boulders, gravel and sand in the filter

The washed sand was then poured into the drum to a varied depth of 30 cm, 40 cm and 50 cm on top of the gravel support (Fig. 3). The filter operated by pouring the wastewater into the drum (with material set up) through the diffuser bowl for the three different depths and flow-through rates per square metre (m^2) of the filter media.

A diffuser was designed to ensure even distribution of the influent (wastewater) onto the filter bed. It also helps to trap the large solid particles in the wastewater (Fig. 4). For each of the depths investigated, a minimum of 21 days was allowed for the *Schmutzdecke* to develop and mature, and for the water particles to travel through the sand bed before the filtrate was collected to be tested for the parameters being investigated.

Investigating effective size

This setup, three tanks, the first setup consists of fine sand with d_{10} value of 0.45 mm while the second setup has sand with d_{10} of 0.27 mm (Fig. 5). The boulders were first washed and placed into the tanks A and B followed by the gravels, to serve as the sand support. Washed sand formed the upper layers of both setups. The third tank was an empty tank with no boulders, gravels and sand aggregates.

Using the dispenser to let water into the system

Water filling the pore spaces

Supernatant water upon fresh set up (Day 1)

Change in supernatant water as schmutzdecke develops (Day 14)

Fig. 4 SSF wastewater filtration process

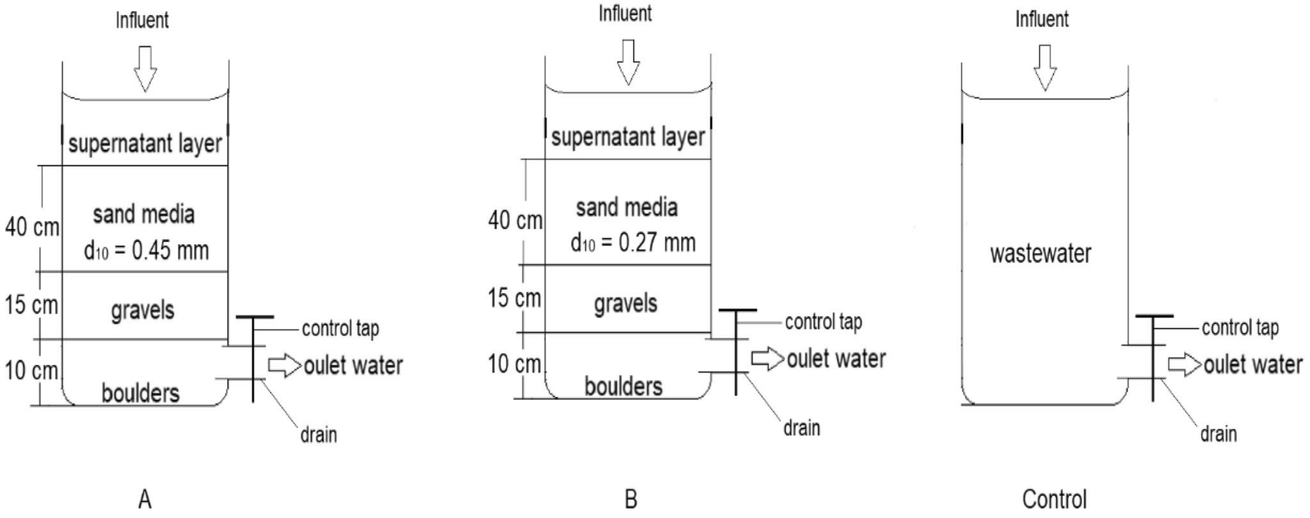

Fig. 5 Slow sand filter arrangement for investigating effective size (D_{10})

All three tanks had PVC pipes fixed to convey the water from the underdrain into the outlet. The perforated pipes also help to reduce the loss of sand from the system. A stopper was provided at the base to allow for easy removal of the water from the tank (Fig. 6). The stopper also regulated the flowrate of effluent water.

Wastewater sampling and test

The wastewater samples were collected in two sterilised 500-mL test bottles from a drain at Kawukudi. HNO_3 was added to each sample and immediately, the samples were placed in a cooler with iced blocks to maintain the temperature at 4 °C before transporting to the Ecology Laboratory of the University of Ghana for the testing of the parameters. The wastewater samples were tested for microbiological and heavy metal parameters for both influent and effluent. The following parameters were tested for microbiological parameters (*E. coli* and Total coliform) and heavy metals (Pb, Cu and Fe). In the detection of the microbiological parameters in the wastewater sample, the Membrane Filter (MF) (CFU/100 mL)—Standard methods for determining heavy metals—Perkin Elmer PIN Accle 900 T Graphite Atomic Absorption Spectrophotometer (AAS) was used.

Statistical method and analysis

The statistical method used in analysing the results of this experimental study was one-way ANOVA. The level of significance (α) was set at 0.05. The analysis was done using Microsoft Excel.

Investigating optimal depth

There was one independent variable (depth of sand media) with three levels (30 cm, 40 cm and 50 cm) and one dependent variable (% Removal) at three levels of filtration rates (215 L/h m^2, 399 L/h m^2 and 664 L/h m^2) for each depth of sand media. The following hypothesis was formulated:

> H_0: There are no statistically significant differences in the percentage removal of pollutants at the three different depths of sand bed. Mathematically, $H_0 = U_{30} = U_{40} = U_{50}$.
>
> H_1: There are statistically significant differences between the percentage removal of pollutants at the three different depths of sand bed. Mathematically, $H_1 \neq U_{30} \neq U_{40} \neq U_{50,}$

where U_x represents the mean percentage removals at the selected depths (30 cm, 40 cm and 50 cm).

Investigating effective size

There was one independent variable (effective size) and one dependent variable (% Removal). There were two d_{10} values and two tests were carried for each d_{10} (one before the *Schmutzdecke* was formed and the second test after the *Schmutzdecke* was formed). The following hypothesis was formulated:

> H_0: There are no statistically significant differences in the percentage removal of contaminants for d_{10} values in the experiment. Mathematically, $H_0 = U_A = U_B = U_C$.

Fig. 6 The wastewater filtration setup at the Agricultural Engineering Workshop

> H_1: There are statistically significant differences between the percentage removal of contaminants for d_{10} values in the experiment. Mathematically, H_1: at least one of the means is different.

where U_y represents the mean removal of contaminants for tanks A, B and C.

To ensure a 95% confidence, an α value of 0.05 is chosen. Given that two effective sizes were tested at three different depths, the degrees of freedom (*df*) becomes (2,3). Therefore, the decision criteria given statistically as *f* critical of 9.55 were obtained from statistical table. With an *f* value computed from data of *df* (2,3) and at an α value 0.05. This means that the null hypothesis is rejected if *f* obtained from computation exceeds f_{crit}.

Results and discussions

Grain size distribution for optimal bed thickness and effective size (D_{10})

The results of the grain size distribution of the sand filter media for optimal bed thickness were carried out to determine, the effective size D_{10} was found to be 0.26 mm and D_{60} was found to be 0.67 mm. This gave a uniformity coefficient, C_u computed to be 2.58 which meets the requirements for SSF as recommended by WHO.

Water quality analysis for optimal bed thickness

Pollutant concentrations were measured for three filtration rates and the results are briefly presented relative to bed thickness.

Biological analysis of wastewater samples at 30-cm sand bed thickness

The number of coliform units per 100 mL in the influent wastewater obtained exceed the WHO [52] permissible limit of $\leq 1.0 \times 10^3$ cfu/100 mL for wastewater irrigation of crops. However, after treatment, the results show there was a 100% removal efficiency of the Total coliform at filtration rates of 215 L/h m^2 and 399 L/h m^2. The *E. coli* removal efficiency was 100% at the filtration rate of 399 L/h m^2. These removal efficiencies agree with the study conducted by Bagundol et al. [23] who reported a 100% removal efficiency for 30-cm depth of sand filter at flow-through rates of 200 L/h m^2 and 400 L/h m^2. In addition, the results of the study by Mwabi et al. [53] also recorded a percentage removal of 99–100% of coliform bacteria from the raw water sample tested.

Biological analysis of wastewater samples at 40-cm sand bed thickness

The influent coliform counts per 100 mL recorded also exceeded the WHO [52] permissible limit of $\leq 1.0 \times 10^3$ cfu/100 mL for irrigation. After filtration at 40-cm bed thickness, the results show significant reduction in the coliform counts in the wastewater with the system recording as high as 100% removal efficiency for both Total coliform and *E. coli*. It was observed that at filtration rates of 215 L/h m^2, 399 L/h m^2 and 664 L/h m^2, there were significantly high percentage removals of 99.9–100% for Total coliform and *E. coli*. These percentage removals were significantly high compared to the 98.4% reported by Muhammad et al. [24] at the 0.4-m depth of sand bed. This is in conformity with the coliform percentage removal of the sand bed depth at 40 cm as reported by Bagundol et al. [23].

Biological analysis of wastewater samples at 50-cm sand bed thickness

Again, the influent coliform counts per 100 mL exceed the WHO [52] permissible limit of $\leq 1.0 \times 10^3$ for irrigation. After filtration, at rates of 399 L/h m^2 and 664 L/h m^2 the effluent recorded significant reduction in the both Total coliform and *E. coli* counts in the wastewater with the system recording between 98.8 and 100% removal efficiency. At the various filtration rates, there were significant removal efficiencies recorded for both parameters. These results agree with the reports that coliform removal efficiencies increase with increasing depth of the sand bed [23, 32].

Heavy metal analysis of wastewater samples at 30-cm sand bed thickness

Trace metal concentrations found in the influent were lower than the WHO [52] permissible limits of 5 mg/L (Pb and Fe) and 0.20 mg/L (Cu) for irrigating crops. A 100% removal efficiency was recorded for Lead and Copper at filtration rate of 215 L/h m^2. At a filtration rate of 399 L/h m^2, the percentage removals of 83.7%, 78.3% and 98.5% were recorded for Pb, Fe and Cu, respectively. A low percentage of 34.9% was recorded for Fe at the filtration rate of 215 L/h m^2 for the depth of 30 cm. The values at 664 L/h m^2 were, however, below detectable limits (BDL).

Heavy metal analysis of wastewater samples at 40-cm sand bed thickness

The results show significant reduction in the heavy metals concentration in the filtered water with as high as 98.3%, 86.3% and 100% removal efficiencies for Pb, Fe and Cu, respectively. The percent removal efficiency of Cu metal was significantly high at this bed thickness recording more than 90% removal in concentration. The percentage removal efficiencies of this bed thickness is significantly high compared to the 31.9% (Cu) recorded in Mbir and Tetteh-Narh [54]. These results indicate the effectiveness of the sand bed of depth 40 cm in the efficient removal of these trace elements in the influent wastewater. The removal of Fe at high filtration rate of 664 L/h/m^2 was, however, as low as 46.69% representing the lowest removal efficiency of the heavy metals at this depth. This is consistent with theory because, as the filtration rate increases, the removal efficiency also decreases.

Heavy metal analysis of wastewater samples at 50-cm sand bed thickness

There were significant reductions in the heavy metal concentration in the effluent with as high as 100% removal efficiencies for all three metals analysed. At a filtration rate of 664 L/h m^2, Fe recorded as low as 53.81% at 50-cm bed thickness. However, according to Khatri et al. [55], at 60 cm of sand bed thickness, there was 90.2% removal efficiency.

Average percentage removal of contaminants

The average percentage removal of Total coliform, *E. coli*, Lead, Iron and Copper for the different sand bed thickness of 0.30 m, 0.40 m and 0.50 m is presented in Table 3. According to Bagundol et al. [23] and Thomas and Kani [32], the coliform removal efficiency increases as the depth of the sand bed is increased. The increasing high removal efficiencies recorded may be due to the maturing of the *Schmutzdecke* thus increasing the biological activity of the filter is enhanced with increasing filter depths. Hence, the microorganisms and other particles have to travel longer distance through the sand. Some of these microorganisms gets trapped between sand grains, while others are adhesively held onto the sand grains. Thus, a higher removal efficiency is expected at deeper depths of the sand bed [24, 32, 38]. The high percentage removals of the Total coliform and *E. coli* from the wastewater means reduced risk of coliform would be found in the effluent irrigated vegetable after harvest.

The removal efficiency of the heavy metal concentration can be attributed to the adsorption of the heavy metals into the *Schmutzdecke* and adhesion to the sand grains in the sand media [56]. The average removal efficiencies of 37.7–84.1% of the sand filter for Fe confirms the results of Mbir and Tetteh-Narh [54] who reported a 38.1% removal efficiency and Khatri et al. [55] who reported 90.15% removal efficiency at 0.60 m of sand bed thickness. However, these results are comparably low compared to 97.9–99.9% reported by Zhang et al. [56].

In addition, the average removal efficiencies of 61.2–98.8% for Pb show an improvement upon the 31–61% reported by Zhang et al. [56] but Mbir and Tetteh-Narh [54] reported 100% removal efficiency when activated charcoal layer was used. Further, the average removal efficiency of 66.2–85.3% recorded for Cu also shows an improvement upon 32.8% reported by Mbir and Tetteh-Narh [54]. The low removal efficiencies may be due to the fact that the sand bed thickness of 0.30 m was small and the sand media was unable to adhesively bind the trace metals to itself due to higher the concentrations in the water sample than the media can remove. But generally, Fe is best removed from water by oxidation of Fe^{2+} to Fe^{3+} which precipitates. Fig. 7 shows a graph of average removal efficiencies at different bed thickness.

Water quality analysis for effective sizes

For each of the effective sizes 0.45 mm and 0.27 mm, the wastewater samples were tested before and after the formation of the *Schmutzdecke* at the flowrate of 0.105 m^3/h and conventional hydraulic loading rate of 0.1 m/h.

Biological analysis of wastewater sample before *Schmutzdecke* formation

Results before the formation of the *Schmutzdecke* showed that the influent concentration of Total coliform counts of 1.73×10^3 cfu/100 mL exceeded WHO [52] permissible limit of 1×10^3 cfu/100 mL while the *E. coli* recorded a lower count of 3.3×10^2 cfu/100 mL relative to the WHO permissible limit. Upon treatment, there were significant reductions in Total coliform and *E. coli* counts with removal efficiencies of 90.1% and 87.9%, respectively, for 0.45 mm effective size sand media. The setup with sand media of effective size of 0.27 mm recorded the highest removal efficiencies of 98.3% and 96.7% for Total coliform and *E. coli*, respectively. The control setup also showed significant removal efficiencies of 71.1% and 93.3% removal efficiencies for Total coliform and *E. coli*, respectively.

Table 3 Percentage removal of contaminants at different thickness of sand bed

Bed thickness (m)	Average percentage removal				
	Total coliform	*E. coli*	Pb	Fe	Cu
0.30	66.67	33.33	61.23	37.73	66.17
0.40	99.97	99.99	74.40	70.69	96.67
0.50	100	99.54	98.80	84.07	85.33

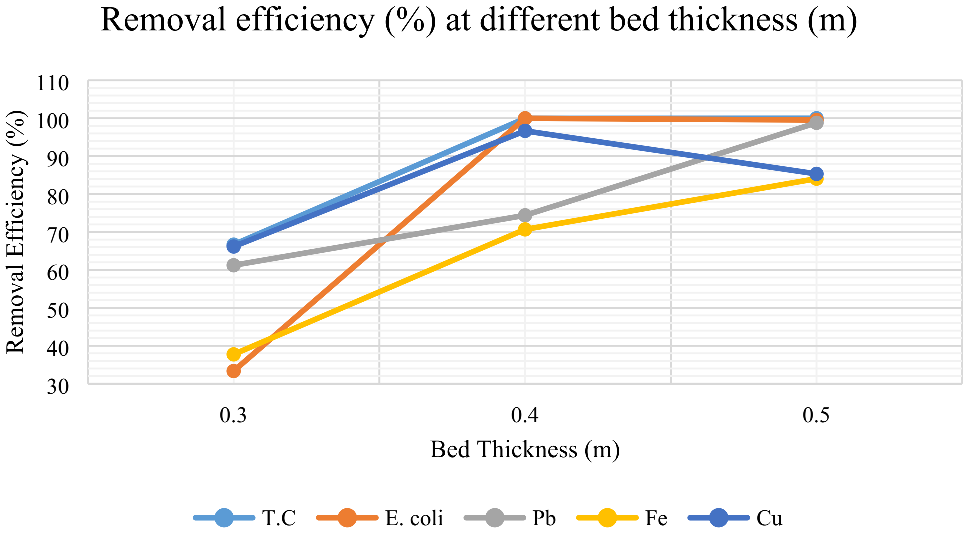

Fig. 7 Average removal efficiencies of Total coliform, *E. coli*, Pb, Fe and Cu at different bed thickness

Biological analysis of wastewater sample after *Schmutzdecke* formation

There was a significant reduction in the coliform counts in wastewater with the system recording as high as 100% removal efficiency each for Total coliform and *E. coli* for d_{10} of 0.27 mm. The filter with d_{10} of 0.45 mm also recorded a 100% removal of *E. coli* and 95% removal of Total coliform. The control recorded a 100% removal of *E. coli* and 75% removal of Total coliform.

Heavy metal analysis of wastewater sample before *Schmutzdecke* formation

The initial concentration of heavy metals in the wastewater sample was 0.34 mg/L for Pb, 0.04 mg/L for Cu and 3.24 mg/L for Fe, respectively. However, it was noted that these concentrations were below WHO [52] permissible limits of 0.2 mg/L for Cu and 5 mg/L for Pb and Fe.

There were no traces of Pb in the effluent for all three setups representing a 100% removal efficiency. For both effective sizes, Cu was completely removed with the control showing a 43.90% removal. The percentage removal of Fe was 24.28%, 37.94% and 23.29% for d_{10} 0.45 mm, 0.27 mm and control experiment, respectively. The low percentage removals may be due to the fact that Fe is better removed from water by means of oxidation [57].

Heavy metal analysis of wastewater sample after *Schmutzdecke* formation

After the *Schmutzdecke* formation, there was a 100% removal of Pb and Fe for the selected effective sizes while the control experiment recorded a 100% removal of Pb and 34.59% removal for Fe. This low percentage removal for Fe can be attributed to adsorption to the container and precipitation due to reactions between the wastewater and the atmospheric gases [58]. There were, however, no traces of Cu in the influent and effluent water samples.

Removal of contaminants

The results show an improvement in the water quality after treatment using the slow sand filter. It was observed that the effluent quality attains higher percentage removal of heavy metals after the formation of the *Schmutzdecke*. This highlights the importance of the adsorption that takes place in the *Schmutzdecke*. In addition, it affords the opportunity for microbes to feed on the waste in the wastewater, thereby reducing its concentration.

Removal efficiency of sand filter with effective size of 0.45 mm

There was significant removal of contaminants in the wastewater after filtration with sand media of $d_{10} = 0.45$ mm before and after the formation of the *Schmutzdecke*. In the removal of *E. coli*, the removal efficiencies of 90.1% (before formation of *Schmutzdecke*) and 95% (after formation of *Schmutzdecke*) of the filter were consistent with the removal efficiencies of 96.7–99% reported by Muhammad et al. [24] for sand media with $d_{10} = 0.45$ mm. The removal efficiencies of Total coliform for before and after the formation of *Schmutzdecke* at the same effective size were 87.9% and 100%. This was also consistent with 96.4–98.6% reported despite the slight reduction. This confirms the feasibility of removing coliforms in wastewater using sand media of $d_{10} = 0.45$ mm. The performance of the filter with sand media of $d_{10} = 0.45$ mm in the removal of Pb, Cu and Fe was significant and can be attributed to the adhesion onto sand grains and adsorption into the *Schmutzdecke*. The removal efficiencies of 100% recorded is in line with the 99.6% (Cu) and 100% (Pb) reported by Muhammad [59] despite using sand media of $d_{10} = 0.32$ mm.

Removal efficiency of sand filter with effective size of 0.27 mm

The *E. coli* removal increased from 96.7% (before *Schmutzdecke* formation) to 100% (after *Schmutzdecke* formation) with sand media of $d_{10} = 0.27$ mm. These removal efficiencies were consistent with the 100% reported by Bagundol et al. [23] at d_{10} between 0.16 mm and 0.30 mm. From a removal efficiency of 98.3% (before *Schmutzdecke* formation), the Total coliform removal increased significantly to 100% (after *Schmutzdecke* formation). The overall coliform removal from the water was observed to recur in the filter after the maturation of the *Schmutzdecke*. The significantly high removal efficiencies recorded have been found to verify the 99.3% and 99.6% reported by Muhammad et al. [24] for the sand media with d_{10} of 0.35 mm and 0.20 mm, respectively. The filter still achieved significantly high removal efficiency levels for the heavy metals (Pb, Cu and Fe) investigated before and after the *Schmutzdecke* was formed. The results of contaminant removal with sand media of $d_{10} = 0.27$ mm were slightly better than sand media with $\mathrm{d}_{10} = 0.45$ mm.

Control experiment

The control setup also recorded some reduction in the contaminants level. The reduction in biological parameters in the control shows that external factors in the environment also play a role in the removal of pollutants in wastewater. The reduction in coliform counts can be as a result of microbial degradation that took place during the residence time.

The reduction in heavy metal contaminants concentration [100% (Pb), 43.90% (Cu) and 23.29% (Fe)] can be as a result of adsorption to container, reactions that took place between the wastewater and the environment (atmospheric gases) over time and precipitation [58, 60]. The concentration of samples that remained below detectable levels implies that the heavy metal was not introduced into the sample from other external sources.

Statistical analyses

A one-way Analysis of Variance (ANOVA) was conducted to compare the effect of the selected thickness (30 cm, 40 cm and 50 cm) of sand bed and effective sizes (0.45 mm and 0.27 mm) on the efficient removal of contaminants from the water. The complete table of ANOVA results can be found in the appendix section.

Analysis of bed thickness data

An analysis of the results showed that the effect of the selected sand bed thicknesses on the efficient removal of coliforms from the wastewater sample was significant for Total coliform and *E. coli* (see Tables 4 and 5 in appendix). In addition, the analysis of the results of heavy metal removal showed that the effect of these sand bed thicknesses on the efficient removal of Pb, Fe and Cu from the water were also significant (see Tables 6, 7 and 8 in appendix). Therefore, the null hypothesis is rejected. This means that the removal of contaminants from the wastewater is increased as the sand bed thickness is increased.

Analysis of effective size data

The ANOVA results show that there was significant difference in the removal efficiency of *E. coli* between $d_{10} = 0.45$ mm and 0.27 mm (see Table 9 in appendix). Hence, the null hypothesis is rejected. However, the results obtained (see Tables 10, 11, 12 and 13 in appendix) for Total coliform, Cu, Pb and Fe show that there were no significant differences in the removal efficiencies between sand media of $d_{10} = 0.45$ mm and 0.27 mm. For Total coliform, Cu, Pb and Fe, we fail to reject the null hypothesis which means that there are no significant differences in the removal efficiency of both sand media of $d_{10} = 0.45$ mm and 0.27.

Conclusion

The treatment of wastewater to be used for irrigation purposes using a relatively low-tech slow sand filter is feasible and can be adopted by small-scale vegetable farmers whose main source of water for irrigating their crops is the wastewater from the drains. This is because the efficiency of the slow sand filter to remove the parameters analysed; *E. coli*, Total coliform, Pb, Fe and Cu varied and were significantly high at sand bed thicknesses of 40 cm and 50 cm. In addition, there was a significantly high removal of the parameters for both sand media of effective sizes, 0.27 mm and 0.45 mm. However, the SSF with an effective size of 0.27 mm obtained slightly better results in the removal of the contaminants. It was established that with a minimum sand bed thickness of 40 cm and sand media of effective sizes up to 0.45 mm, wastewater from the drain can be treated for irrigation of vegetable crops. The implication is that the extra cost of acquiring extra sand with the aim of improving wastewater quality can be saved.

It must be indicated that investigation of effective sizes was subsequent to establishing that the thicker the bed depth, the higher the removal efficiency of contaminants and so both the experiments were conducted at different times. The combined effects of sand bed depth and effective sizes are being investigated and this will be later reported.

Appendix: ANOVA results

See Tables 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13.

Part A: Bed thickness.

Part B: Effective size.

Table 4 ANOVA results for *E. coli*

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	10750.67	1	10750.67	18.13	0.001	4.49
Within groups	9486.68	16	592.92			
Total	20237.34	17				

Table 5 ANOVA results for Total coliform

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	6369.44	1	6369.44	6.33	0.02	4.49
Within groups	16094.70	16	1005.92			
Total	22464.14	17				

Table 6 ANOVA results for Lead

Source of Variation	*SS*	*df*	*MS*	*F*	*p* value	F_{crit}
ANOVA						
Between groups	6546.73	1	6546.73	11.06	0.004	4.49
Within groups	9469.92	16	591.87			
Total	16,016.66	17				

Table 7 ANOVA results for Iron

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	2627.64	1	2627.64	4.50	0.05	4.49
Within groups	9351.97	16	584.49			
Total	11979.61	17				

Table 8 ANOVA results for Copper

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	8213.77	1	8213.77	14.51	0.002	4.49
Within groups	9054.88	16	565.93			
Total	17268.65	17				

Table 9 ANOVA results for *E. coli*

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	736.03	2	368.01	52.308	0.005	9.552
Within groups	21.11	3	7.04			
Total	757.13	5				

Table 10 ANOVA results for total coliform

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	19.69	2	9.84	0.292	0.766	9.552
Within groups	101.24	3	33.75			
Total	120.92	5				

Table 11 ANOVA results for copper

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	1049.07	2	524.535	0.144	0.872	9.552
Within groups	10963.61	3	3654.535			
Total	12012.68	5				

Table 12 ANOVA results for lead

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	0	2	0	65,535		9.552
Within groups	0	3	0			
Total	0	5				

Table 13 ANOVA results for Iron

Source of variation	SS	*df*	MS	*F*	*p* value	F_{crit}
ANOVA						
Between groups	1834.19	2	917.10	0.567	0.618	9.552
Within groups	4856.33	3	1618.78			
Total	6690.52	5				

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