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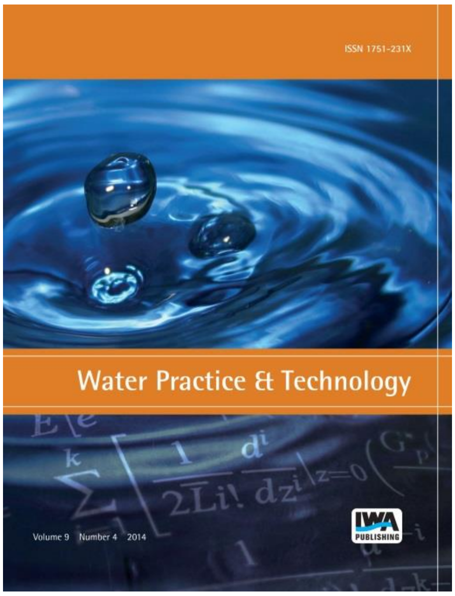

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Performance of constructed wetland integrated with sand filters for treating high turbid water for drinking

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Abstract

The feasibility of constructed wetland integrated with sand filters (CW-SFs) for treating high turbid water for drinking was investigated. Turbid water of >1,000 NTU from Nadosaito dam in Monduli District, Tanzania was used. Along with turbidity; faecal coliform (FC), chemical oxygen demand (COD), total suspended solids (TSS) and nitrate removal were investigated. Furthermore, determination of optimal retention time for pollutants removal to acceptable levels was assessed at retention times of 0.5 to 5 days. Horizontal subsurface flow constructed wetland (HSSFCW) was used as pretreatment stage prior to biosand or slow sand filters. Results showed that HSSFCW produced effluent turbidity of <10–50 NTU at retention time of 3 days. Moreover, integrated CW-BSF needed a total retention time of 5 days to produce effluent of turbidity (0 NTU), FC (0 CFU/100 ml), COD (6.25 mg/L), TSS (0.5 mg/L) and nitrate (4.2 mg/L) whereas, CW-SSF needed 7 days to produce effluent of turbidity (0.6 NTU), FC (0 CFU/100 ml), COD (6.5 mg/L), TSS (1 mg/L) and nitrate (1.79 mg/L), which met drinking water standards of Tanzania Bureau of Standards (TBS) and World Health Organization (WHO). CW-BSF showed better performance than CW-SSF therefore, its application can enhance the availability of potable water in Tanzania rural communities.

Key words: constructed wetland, retention time, safe water, sand filters

INTRODUCTION

In Rural and peri-urban areas of Tanzania, the use of unsafe drinking water from surface water sources like rivers, lakes, earthen dams, wells and open springs is not optional due to limited piped water supply (Mohamed *et al.* 2016). Therefore, to limit the outbreak of waterborne diseases it is vital to eliminate pathogens, organic matters, suspended solids and chemicals that can have serious human health effects (Gupta & Chaudhuri 1995; Groendijk & de Vries 2009; Mahmood *et al.* 2011). Point of use (POU) house hold water treatment technology can help individuals without access to safe and clean drinking water to treat water at their homes thus getting rid of waterborne diseases (Sobsey 2002; Sobsey *et al.* 2008; Jenkins *et al.* 2011; Kennedy *et al.* 2012).

In developing countries, common POU current used in homes include, biosand filters (BSF) and slow sand filter (SSF) (Sobsey *et al.* 2008). About 500,000 people worldwide depend on BSF for safe drinking water supply and its efficiency on faecal coliform (FC) and *Escherichia coli* removal have been documented (Duke *et al.* 2006; Stauber *et al.* 2006; Elliott *et al.* 2008). The growing interest to application of sand filters in water quality improvement is due to their low cost, convenient operation and easy maintenance while achieving high treatment efficiency (Logsdon *et al.* 2002; Nassar & Hajjaj 2013; Haig *et al.* 2014). These attributes make sand filters as cost effective technology to treat contaminated water in rural areas (Aslan & Cakici 2007; Langenbach *et al.* 2009).

The removal mechanisms of water contaminants by sand filters are purely physical, chemical and biological processes (Langenbach *et al.* 2009; Bauer *et al.* 2011; Ijadunola *et al.* 2011; Haig *et al.* 2014). Basically, gravity flow is the main operating force for influent flow (Young-Rojanschi & Madramootoo 2014). Physico-chemically raw water contaminants such as organic matter, suspended matters are removed by screening, sedimentation, adsorption, straining, adhesion, diffusion and flocculation (Mwiinga 2011; Bagundol *et al.* 2013). Furthermore, formation of biological layer by microorganisms on surface of sand bed facilitates the biological removal of water contaminants like pathogens through predation, scavenging, adsorption and bio-oxidation (Joubert & Pillay 2008; Hsieh *et al.* 2010; Elliott *et al.* 2011; Mwabi *et al.* 2013; Haig *et al.* 2014). According to Elliott *et al.* (2011), proteolytic enzymes produced by microbial exoproducts are responsible for pathogen reduction. Normally sand filters removal rates depend on filter depth, sand type, sand size and filtration rate (Abudi 2011). Long filter depth increase travel distance thus high pollutants removal rate (Ellis & Wood 1985).

Several authors have reported the efficiency of sand filters in removing different contaminants in water to be between 90 to 99% (pathogenic bacteria) by 85–90% (viruses), 87–96% (turbidity), 94–99% (nitrate) and >99.9% (protozoans) (Stauber *et al.* 2006; Aslan & Cakici 2007; Elliott *et al.* 2008; Jenkins *et al.* 2011; Mahmood *et al.* 2011; Kennedy *et al.* 2012; Mwabi *et al.* 2013; Young-Rojanschi & Madramootoo 2014). Nevertheless, their treatment efficiency can decrease with high turbid water (>10–50 NTU), high organic loading and high amount of microorganisms in raw water because, they tend to clog the filters and decrease the filter run time and treatment efficiency (Logsdon *et al.* 2002; Ray & Jain 2011). Therefore, the need for a reliable pretreatment technology before using sand filters is inevitable.

Coagulation and flocculation by inorganic and organic compounds are amongst pretreatment technologies, which are used to clean high turbid water however, they are not cost effective to rural communities (Silva *et al.* 2013; Ramavandi 2014). Furthermore, they cannot remove other water contaminants like heavy metals, organic materials, pesticides, oil and excess nutrients. Roughing filters have also been used prior to sand filters for water turbid removal (Nkwonta & Ochieng 2009; Mwiinga 2011). However, it is generally limited to turbidity removal due to absence of macrophytes as it has been reported that vegetated system perform better in FC removal than unplanted system (Davies & Bavor 2000). Normally, vegetation helps in settling of fine particles and their associated bacteria, but also increases the physical contact area between the bacteria, plant roots and the wetland substrate (Gerba *et al.* 1999). Moreover, plants roots produce antibacterial which aid in pathogens removal (Vymazal 2005) and stabilization of the hydraulic conductivity thus prevent filter clogging (Cordesius & Hedstrom 2009). Therefore, constructed wetland can be considered as viable pretreatment technology that can reduce water turbidity and other pollutants found in water prior to sand filters.

Horizontal subsurface flow constructed wetland (HSSFCW) is a robust system that need low energy, easy operation and maintenance thus allowing decentralization of water treatment system (Vymazal 2009; Wu *et al.* 2014). The system combines physical, chemical and biological processes to remove water pollutants (Sundaravadivel & Vigneswaran 2001; Stottmeister *et al.* 2003). In this system physico-chemically pollutants are removed by sedimentation, filtration, adsorption, precipitation, sorption, photochemical oxidation, disinfection and volatization (Karim *et al.* 2004). Biologically water pollutants are removed by predation, scavenging, natural die-off, nitrification, denitrification, algae and plant uptake, aerobic and anaerobic biodegradation (Karim *et al.* 2004; Vacca *et al.* 2005; Vymazal 2005; Díaz *et al.* 2010).

Reports from several studies indicate that the efficiency of HSSFCW system to reduce pollutants in water ranges between 80–90% (chemical oxygen demand (COD)), 50–80% (turbidity) and >90% (FC) (Cordesius & Hedstrom 2009). On other hand it has reduced 95.9% and 90.6% for tannins and COD, respectively, form tannins extracting company (Njau & Renalda 2010). Also, in a study conducted at the University of Dar es salaam (Tanzania) demonstrated the removal efficiency of 93.2 ± 6.13%, 92.6 ± 6.05%, 71 ± 6.2%, 58.1 ± 135.56% and 40.1 ± 14.5% for FC, *Escherichia coli*, organic matter, nitrate and phosphate, respectively (Mairi *et al.* 2013). This study aimed to assess the removal efficiency of physico-chemical and biological pollutants from high turbid water by integrating constructed wetland and sand filters and justify the possible application of such technology in rural communities to increase the availability of potable water.

MATERIALS AND METHODS

Study area

The experimental integrated treatment system was set and executed in the ventilated green house and water quality Laboratory at Nelson Mandela African Institution of Science and Technology (NM-AIST) in Arusha region Tanzania. The area is located at Latitudes 03°24′S, Longitude 036° 47′E with elevation of 1,204 m above sea level. HSSFCW was set in the green house while the integrated parts of sand filters were set in water quality laboratory. Turbid water of >1,000 NTU from Nadosaito dam in Monduli district, Tanzania was used in this experiment.

Experimental design and setup

The systems used in this study were composed of HSSFCW, SSF and BSF.

Horizontal subsurface flow constructed wetland

HSSFCW was constructed by concrete with a dimension of 140 cm length, 60 cm width and 100 cm depth. It was filled with aggregates of 12.5–20 mm with average porosity of 0.35 at 60 cm depth and planted with *Typha latifolia* as shown in Figure 1. Raw water with average annual turbidity value of >1,000 NTU from Nadosaito dam was collected and stored in a plastic tank of 2,000 L then, allowed to flow in HSSFCW as pretreatment stage before feeding to the sand filter units. Influent was set at 60 cm then, allowed to flow horizontally before exiting at 50 cm below the gravel depth after each treatment time. CW was operated at retention time of 0.5,1,2,3,4 and 5 days with a volumetric flow rate of 180 to 18 ml/min whereby, after each treatment time the collected effluent was fed in SSF and BSF.

Slow sand filter

SSF unit used was constructed at NM-AIST in collaboration with Purdue University by using 20 L plastic pails. The filtration unit consisted of a stack of two 20 L plastic pails (two, for adequate

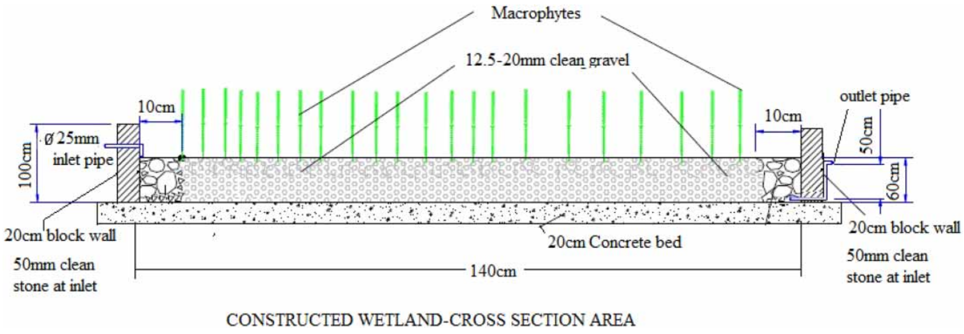

Figure 1 | Cross section area of HSSFCW.

total depth of filtration) in which each pail had about 20 cm depth of sand as shown in Figure 2. At the bottom of each filter a porous plate was used to replace the traditional gravel layers followed by sand with average grain size of 0.4 mm. In each pail, food-grade plastic tubing was used to convey the filtered water from the porous plate up to a hole on the side of each pail whereby, through capillarity and gravity, water was conveyed from the top pail to the bottom pail or from the bottom pail to the collection pail. The level of water above the sand was controlled by the location of the hole on the side of each pail, which was placed about 2 cm above the top of the sand layer. This helped to maintain the effective thickness of biolayer that can be only 2 cm in depth (Campos *et al.* 2006). SSF was run as continuous flow experiment with filtration rate of 0.02 m/hr to 0.002 m/hr translating to retention times of 0.5 to 5 days, respectively.

Biosand filter

BSF was prepared at NM-AIST by using plastic container, gravels and sand as shown in Figure 3. During BSF preparation sand of average grain size of 0.2 mm was sieved by mosquito net wire to remove dirty materials, thereafter washed with distilled water and left to the sun for drying. Gravels were prepared by sieving the crashed aggregates by using tophi net wire so as to obtain gravel size of 12.5 mm and 6.25 mm diameter which were also washed with distilled water then allowed to dry. Column packing was carried out by using plastic container of about 75 cm where, 4.5 kg of 12.5 mm gravels were packed at the bottom of the container at depth of 5 cm followed by other 4.5 kg gravel of 6.25 mm at 5 cm depth. Size wise packing of gravels is crucial as it hold sand filter from displacement (Mwabi *et al.* 2013). Thereafter, about 45 kg of sand was packed at a depth of

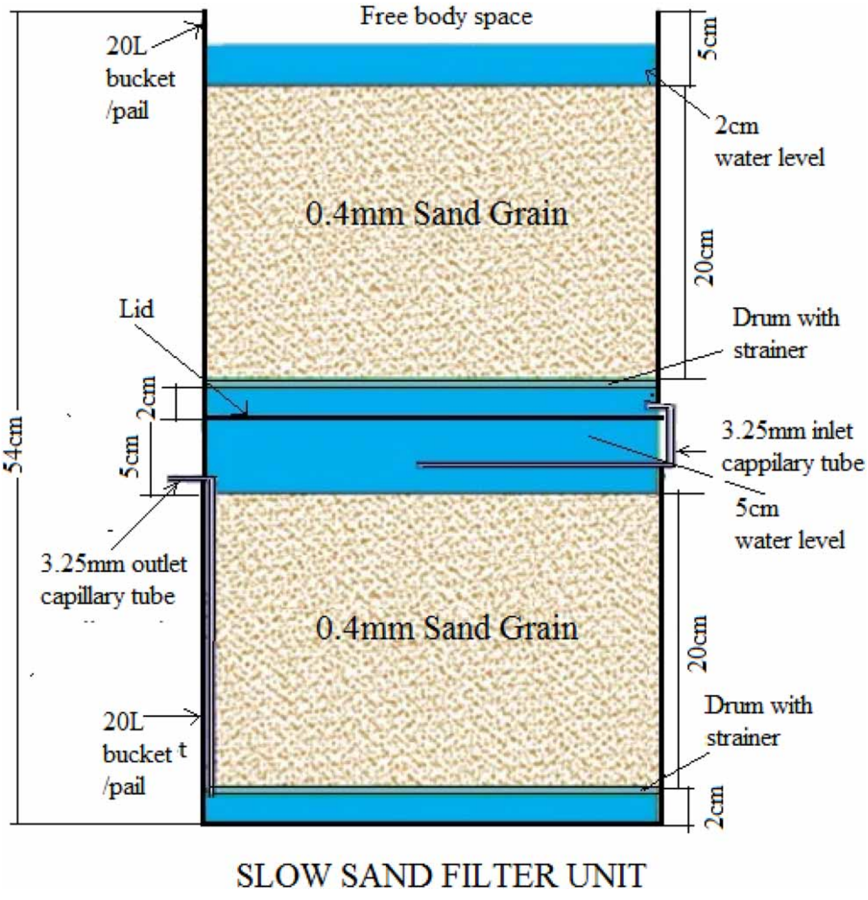

Figure 2 | Cross section area for SSF.

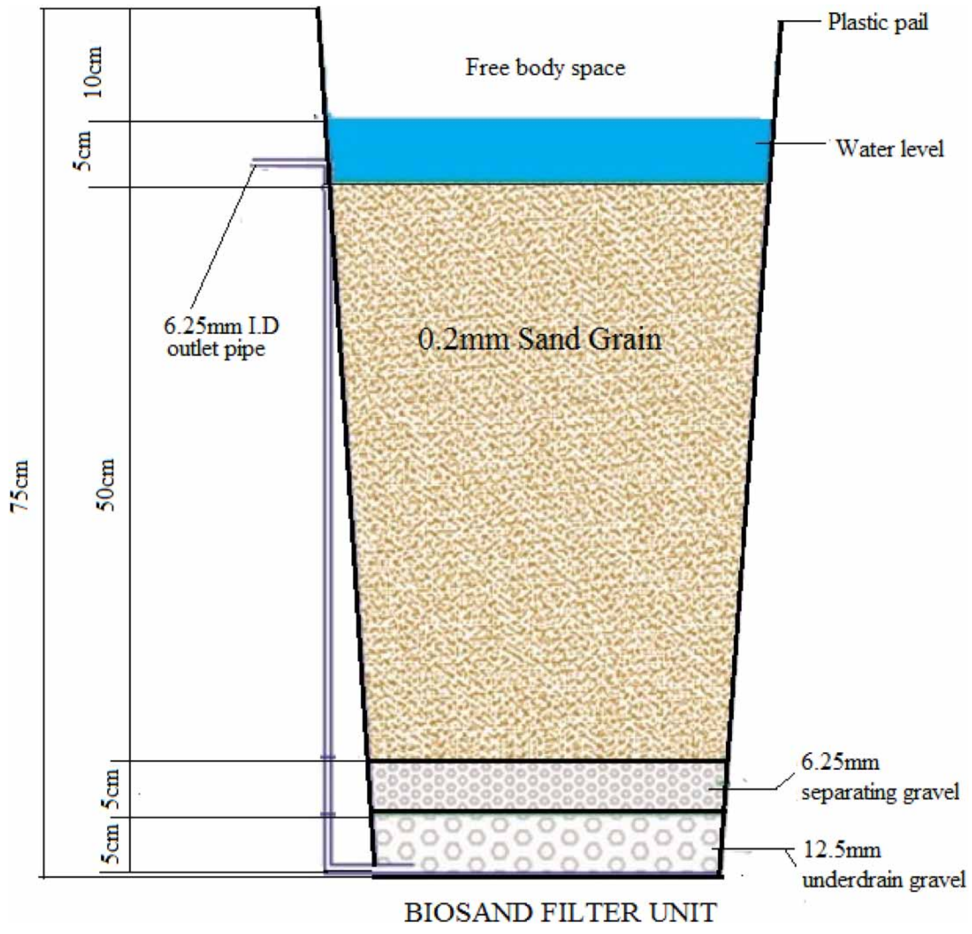

Figure 3 | Cross section area for BSF.

40 cm, during packing sand and water were poured simultaneously so as to remove air spaces within the sand filter column. Water level was maintained at 5 cm above the sand by adjusting the discharge tube so as avoid dewatering. Then the filter was left for two weeks to allow the development and ripening of biolayer by feeding it with raw water from Themi River. Filter column under this experiment had about 50 cm with water holding capacity of 10 L that was fed as batch volume. BSF was operated intermittently with batches at retention times of 0.5,1,2,3,4 and 5 days.

Differences between SSF and BSF

Basically sand filters use the same filtration method to filter water, but also have active biolayer and use gravity to push water through the filtration sand. However, BSF differs from SSF in terms of operation design, cleaning and purpose. BSFs are designed to operate intermittently in which batch mode feeding of raw water is applied between treatment times whereas, SSFs are designed for continuous flow operation in which the influent is allowed at different filtration rate. During cleaning BSFs are cleaned by 'swirl and dump' technique but SSFs are cleaned by removing 1–2 cm of the top sand which is then cleaned and refilled thereafter raw water is fed to allow the development of biolayer. Furthermore, BSFs are purposely made for house hold level or small group water treatment while SSF designed for community or large group water treatment. Therefore this study intended to investigate the effectiveness of the two systems once integrated with HSSFCW in treating high turbid water as schematically shown in Figure 4.

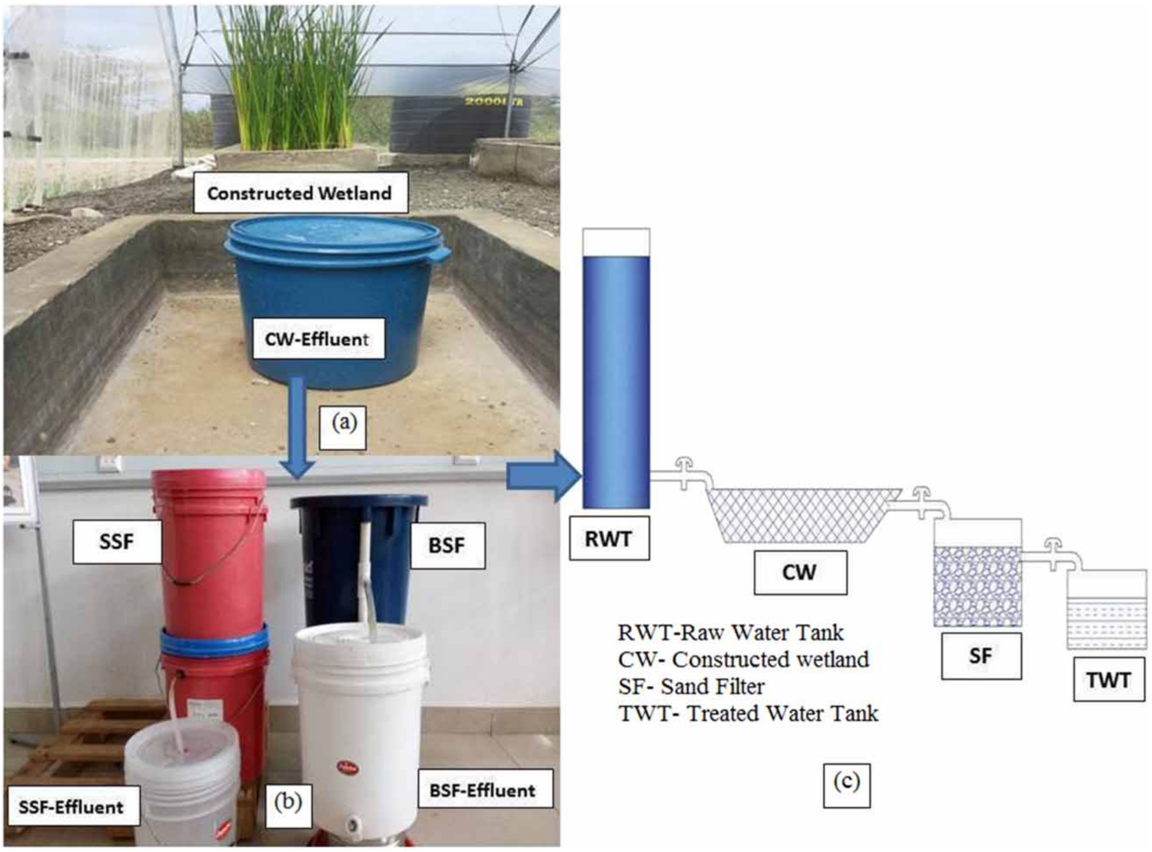

Figure 4 | (a) Constructed Wetland (b) Sand filters (c) Layout of the experimental integrated Constructed wetland and sand filters treatment plant.

Sample collection

Water samples from the integrated system were collected from three points, CW influent, CW effluent or SSF/BSF influents and SSF/BSF effluents. Water samples for physico-chemical analysis were collected by using 500 ml polyethylene sampling bottles. These bottles were washed and rinsed thoroughly with distilled water then re-rinsed three times with the respective water samples before sample collection. Samples for microbial analysis were collected by using 250 ml glass bottles that were first washed and rinsed with distilled water followed by sterilization by autoclaving at 121 °C for 2 hours. Before sampling all bottles were re-rinsed three times with the respective water samples. All samples were stored in ice cool box at 4 °C before laboratory analysis.

Physico-chemical analysis

Physico-chemical parameters like pH, temperature, dissolved oxygen (DO), electrical conductivity (EC) and total dissolved solids (TDS) were determined onsite by Hanna Multiparameter (HI 9829), whereas turbidity was determined by Hanna Turbidometer (HI 93703). The rest of parameters were analysed at NM-AIST laboratory. Total suspended solids (TSS) were analysed by gravimetric method at 105 °C for 1 hour as per standard methods for the examination of water and wastewater (APHA 2012). Nitrate were determined by cadmium reduction method using HACH DR 2800 spectrophotometer while, COD by dichromate digestion method by using Hanna COD and Multiparameter photometer (HI 83099) as described by standard methods for the examination of water and wastewater (APHA 2012).

Microbiological analysis

Microbial water quality was determined by analyzing FC indicator. FC were analysed by membrane filtration method where water samples were filtered through sterilized membrane filter of 0.45 micron pore size and 47 mm diameter. Thereafter, the membrane filters were placed in sterilized petri dishes that contained prepared MFC-agar medium and incubated at 44.5 °C for 24 hours (APHA 2012). This allowed the faecal bacterial indictor to grow into blue colonies that were counted as colony forming unit per 100 ml of analyte (CFU/100 ml).

Statistical analysis

All data were processed in OriginPro software version 8.6 to obtain the trend of water pollutants removal by integrated systems. Descriptive statistics were used to summarize the data using IBM SPSS version 21 and the difference in removal efficiency between the integrated CW-SSF and CW-BSF was estimated by unpaired sample statistical t-test using R-software version 3.21. All the results at $P < 0.05$ were considered statistically significant.

RESULTS AND DISCUSSION

Variation of physico-chemical parameters

The removal of pathogenic bacteria plus other water contaminants depend on biological and chemical reactions that are also affected by environmental factors like temperature, pH and DO.

pH

Chemical and microbial activities taking place in constructed wetland and sand filters are affected by pH. Results from Tables 1–3 show that the influents and effluents pH from the integrated systems were observed to vary depending on the treatment unit. Generally, the pH was found to be decreasing from influent to effluent of CW and increasing from the influent to effluent of SSF and BSF. This trend might be due to anaerobic decomposition of organic matter in the constructed wetland and dissolution of mineral ions in sand bed filter media during infiltration (Mahmood *et al.* 2011).

Table 1 | Physico-chemical water quality from planted CW treatment system

			RT (days)					
Parameter	**Unit**		**0.5**	**1**	**2**	**3**	**4**	**5**
pH	Numeric	Influent	8.37	8.25	8.17	8.15	8.29	8.44
		Effluent	7.31	7.33	7.44	7.45	7.48	7.52
Temp	°C	Influent	21.55	21.64	21.82	21.15	21.6	22.05
		Effluent	24.94	24.2	22.74	23.7	23.15	22.59
DO	mg/L	Influent	4.52	4.48	4.415	4.71	5.12	5.53
		Effluent	3.76	3.55	3.13	3.67	4.11	4.55
EC	µs/cm	Influent	425	421	414.5	409.5	421	428.5
		Effluent	625	578	484.5	663	675	685
TDS	mg/L	Influent	212.5	210.5	207.5	204.5	210.5	214.5
		Effluent	312.5	288.5	242.5	331.5	338	342.5

Table 2 | Physico-chemical water quality from integrated CW- SSF

			RT (days)					
Parameter	**Unit**		**0.5**	**1**	**2**	**3**	**4**	**5**
pH	Numeric	Influent	7.31	7.33	7.44	7.45	7.48	7.52
		Effluent	7.89	7.91	7.96	7.89	7.93	7.99
Temp	°C	Influent	24.94	24.2	22.74	23.7	23.15	22.59
		Effluent	23.74	23.8	23.91	24.58	24.65	24.71
DO	mg/L	Influent	3.76	3.55	3.13	3.67	4.11	4.55
		Effluent	3.51	3.44	3.3	2.62	3.07	3.52
EC	µs/cm	Influent	625	578	484.5	663	675	685
		Effluent	662	596	585	732.5	704.5	756.5
TDS	mg/L	Influent	312.5	288.5	242.5	331.5	338	342.5
		Effluent	331	298	292.5	366.5	352.5	378.5

Table 3 | Physico-chemical water quality from integrated CW-BSF

			RT (days)					
Parameter	**Unit**		**0.5**	**1**	**2**	**3**	**4**	**5**
pH	Numeric	Influent	7.31	7.33	7.44	7.45	7.48	7.52
		Effluent	7.95	7.97	7.97	7.98	7.98	7.98
Temp	°C	Influent	24.94	24.2	22.74	23.7	23.15	22.59
		Effluent	24.00	24.05	24.16	24.5	24.83	25.16
DO	mg/L	Influent	3.76	3.55	3.13	3.67	4.11	4.55
		Effluent	3.68	3.44	2.97	3.16	3.24	3.33
EC	µs/cm	Influent	625	578	484.5	663	675	685
		Effluent	643	590	585	725	761.5	807
TDS	mg/L	Influent	312.5	288.5	242.5	331.5	338	342.5
		Effluent	321.25	295	292.5	362.5	380.5	403.5

Temperature

The rate of physico-chemical and microbial activities in water is affected by temperature variations. Temperature controls the rate of pollutants removal in CW (Kadlec & Reddy 2001; Barea *et al.* 2005) for example, it influences the removal of pathogens in surface and subsurface flow CW (Molleda *et al.* 2008). From Tables 1–3 it was observed that influents had low temperature while effluents had high temperature for CW, SSF and BSF. The trend of temperature increase might be attributed to change in atmospheric weather condition of the experimental set sites that is within the green house and NM-AIST laboratory.

Dissolved oxygen

DO is an important parameter that ascertains physico-chemical and biological activities taking place in water (Efe *et al.* 2005). In CWs and sand filters DO facilitate in degradation of organic matter by aerobic microorganisms. Results from the Tables 1–3 show the decreasing trend of influents to effluents DO concentration for the integrated systems. The observed DO decreasing trend from both integrated systems might be attributed to microbial degradation of organic matters occurring in

CW and sand filters. For instance, Bhatia & Goyal (2014), reported that, presence of rhizosphere in CW macrophytes provide an attachment area of aerobic microorganisms that utilizes DO on degradation of organic matter.

Electrical conductivity and total dissolved solids

EC is the measure of ability of water to conduct electric current. It reflects the presence of dissolved solids and salinity in water. Results from Tables 1–3 show that, EC and TDS were observed to increase from influent to effluent values for CW, SSF and BSF. The general increasing trend of EC and TDS from a pretreatment unit and sand filters might be attributed to dissolution of ions during degradation of water pollutants in the systems.

Effect of retention time on pollutants removal from turbid water by integrated systems

Turbidity removal

Turbidity reflects the inorganic, organic, suspended and colloidal matters present in water that affects water transparency. Results from Figure 5 show that influent turbidity varied between 902 and 1,494.5 NTU with a mean value of 1065.25 NTU, but it was reduced by constructed wetland to 247–2.65 NTU for retention times of 0.5 to 5 days, respectively. In this experiment it was noted that after a retention time of 3 days CW could reduce water turbidity to <10 NTU. Furthermore, the turbidity of the influent to the sand filters was ultimately reduced to 11.01–0 NTU by BSF and 20.25–0 NTU by SSF for retention times of 0.5 to 5 days, respectively. Also in this experiment it was noted that BSF needed a retention time of 1 day whereas SSF needed 3 days to produce effluent of <5 NTU, a value that fall within TBS (5–25 NTU) and WHO standards for drinking water (5 NTU).

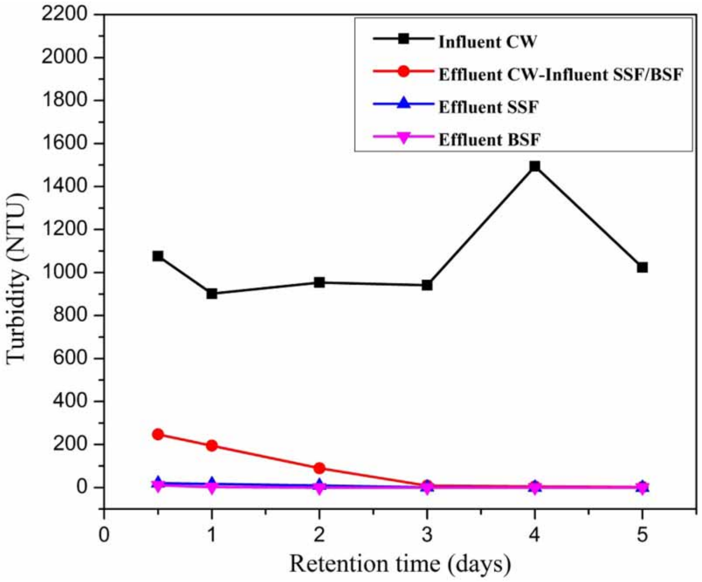

Figure 5 | Variation of Turbidity with time in the influent and effluents of CW-SSF and CW-BSF.

The removal mechanisms of water turbidity in the CW is attributed to sedimentation and filtration facilitated by macrophytes roots that reduce interspaces between gravel by forming dense filter media that is capable of removing suspended particles (Yang *et al.* 2011). Moreover, turbid removal in sand filters is attributed to sedimentation, microbial biodegradation of suspended organic matter and filtration through the sand column.

Statistically unpaired sample t-test showed that there was significant difference in water turbid removal between CW-BSF and CW-SSF $P < 0.05$ ($t = 3.82$, df = 6.64, p-value =0.007). The improved performance of CW-BSF over CW-SSF might be attributed to batch feeding mode in BSF which allowed enough contact time between biolayer and sand column with raw water compared to continuous flow mode in SSF (Ahammed & Davra 2011; Jenkins *et al.* 2011). Moreover, small sand size and long filter depth of BSF compared to SSF might be the addition factor for CW-BSF better performance (Jenkins *et al.* 2011).

Faecal coliform removal

Figure 6 show FC removal by constructed wetland integrated with sand filters. Influent FC varied between 1,075 and 2,250 CFU/100 ml with a mean value of 1577.08 CFU/100 ml but, was reduced by CW to 775–600 CFU/100 ml for retention times of 0.5 to 5 days, respectively. This effluent was used as influent to the BSF and SSF. The FC in the influent to the sand filters were reduced to 225–0.00 CFU/100 ml by SSF and 50–0.00 CFU/100 ml by BSF for retention times of 0.5 to 5 days, respectively. The FC removal by SSF and BSF was observed to improve with retention time. For instance, in this experiment it was seen that the BSF and SSF needed a retention time of 2 and 4 days, respectively, to produce effluent that fall within TBS and WHO standards for drinking water (0 CFU/100 ml).

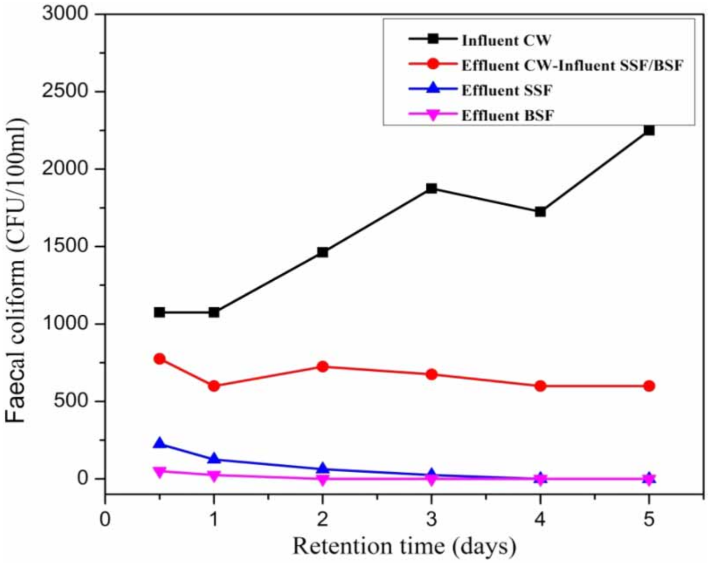

Figure 6 | Variation of FC with time in the influent and effluents of CW-SSF and CW-BSF.

FC removal in constructed wetland is due to the development of biolayer that is colonized by microorganisms that kill other organisms by predation and scavenging (Vymazal 2005). Moreover, adsorption to filter media, filtration, sedimentation and natural die off contributed to FC reduction (Karim *et al.* 2004; Vymazal 2005; Díaz *et al.* 2010). In sand filters; predation, scavenging, resource competition, adsorption and natural die off might have contributed to FC removal (Elliott *et al.* 2011; Mwabi *et al.* 2013; Haig *et al.* 2014). According to unpaired sample statistical t-test, no significant difference in FC removal was observed between CW-BSF and CW-SSF $P > 0.05$ ($t = 1.71$, df = 5.56, p-value = 0.142), suggesting that sand size, long filter depth and batch mode feeding in BSF are not significant factors in FC removal, instead active biolayer and retention time was probably the main removal path.

COD removal

Influent and effluent COD concentration from the integrated systems are presented in Figure 7. The COD influent varied between 24.5 and 35.25 mg/L with mean value of 30.08 mg/L but, was reduced by CW to 22.5–8.25 mg/L for retention times of 0.5 to 5 days, respectively. When this effluent was fed in sand filters, the COD concentration was reduced to 16.5–3.25 mg/L by SSF and 14.25–2.00 mg/L by BSF for retention times of 0.5 to 5 days, respectively. Furthermore, BSF and SSF needed a retention time of 1 and 2 days, respectively, to produce COD effluent <10 mg/L that meets WHO standards for drinking water of 10 mg/L.

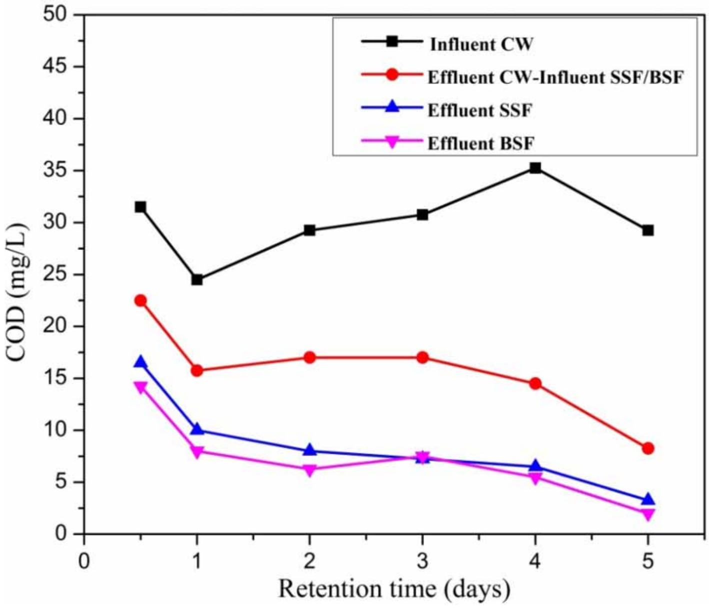

Figure 7 | Variation of COD levels with time in the influent and effluents of CW-SSF and CW-BSF.

The COD removal in integrated systems is attributed to filtration, sedimentation of suspended solids, aerobic and anaerobic degradation of organic matter by microorganisms in CW (Njau & Renalda 2010; Gersberg *et al.* 2015) and in sand filters (Mwiinga 2011; Bagundol *et al.* 2013). Statistically un-paired sample t-test showed that there was no significance different in COD removal between CW-BSF and CW-SSF ($P > 0.05$ $t = 1.22$, df = 10, p-value = 0.249). This means that mechanisms for organic matter removal in sand filters were not affected by the differences between BSF and SSF.

TSS removal

Influent and effluent TSS concentration from the integrated systems are presented in Figure 8. The TSS influent varied between 77 and 138.75 mg/L with mean value of 116.08 mg/L however, this value was reduced by CW to 34.75–4.00 mg/L for retention times of 0.5 to 5 days, respectively. TSS effluent from CW was reduced to 14–0.00 mg/L by SSF and 5.75–0.00 mg/L by BSF for retention times of 0.5 to 5 days, respectively. From these results it was observed that BSF and SSF needed 1 and 3 days, respectively, to lower TSS to <5 mg/L. This is the accepted TSS concentration for drinking water according to WHO standards value of 5 mg/L.

The TSS removal from CW is attributed to sedimentation and filtration of suspended particles by dense network of plant root. Furthermore, TSS removal by sand filters is attributed to biodegradation, particles sedimentation and entrapping in sand filter column. Unpaired sample t-test analysis indicated there was statistical significant difference in TSS removal between CW-BSF and CW-SSF

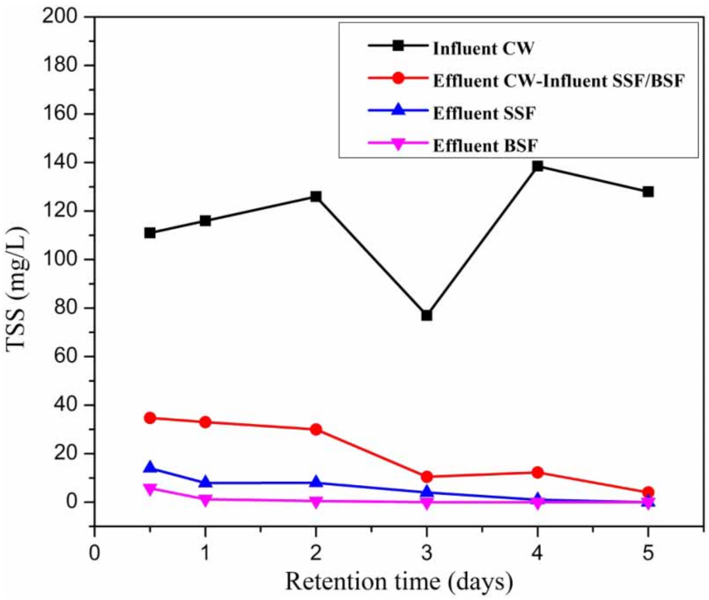

Figure 8 | Variation of TSS with time in the influent and effluents of CW-SSF and CW-BSF.

$P < 0.05$ ($t = 2.72$, $\mathrm{df} = 6.59$, p-value $= 0.031$). The better performance of CW-BSF over CW-SSF in TSS removal is attributed to long filter column, small sand size and long contact time of raw water in BSF due to pause feeding mode.

Nitrate removal

Figure 9 show the influent and effluent nitrate concentrations for the integrated CW-SSF and CW-BSF. Influent nitrate concentration varied between 16.55 and 23.2 mg/L with mean value of 19.8 mg/L was reduced by CW to 14.38–3.9 mg/L for retention times of 0.5 to 5 days, respectively. This concentration was used as sand filters influent and was reduced by SSF to 10.7–0.9 mg/L and by BSF to10.1–0.55 mg/L for retention times of 0.5 to 5 days, respectively. Both BSF and SSF were able to produce nitrate effluent of <10 mg/L after 1 day.

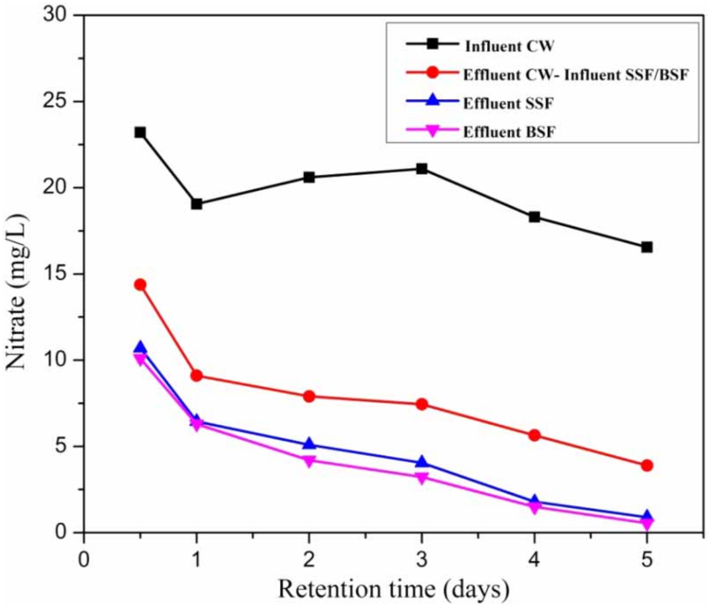

Figure 9 | Variation of nitrate with time in the influent and effluents of CW-SSF and CW-BSF.

The nitrate removal in CW is due to nitrification and denitrification, sedimentation, volatization and plant uptake. However, in sand filters, nitrate removal is attributed to denitrification process and sedimentation in sand column. In this case, unpaired sample t-test showed that there was no significant difference in nitrate removal between CW-BSF and CW-SSF $P > 0.05$ ($t = 0.56$, $\mathrm{df} = 9.96$, p-value $= 0.591$).

Comparison of final effluent quality between CW-SSF and CW-BSF

Turbidity effluent

Figure 10 show the final turbidity effluent from CW-SSF and CW-BSF where, CW-BSF shows better performance over CW-SSF against the total retention time. CW-BSF and CW-SSF needed a total retention time of 4 and 6 days, respectively, to producing water of <5 NTU. This value meets WHO and TBS drinking water standards.

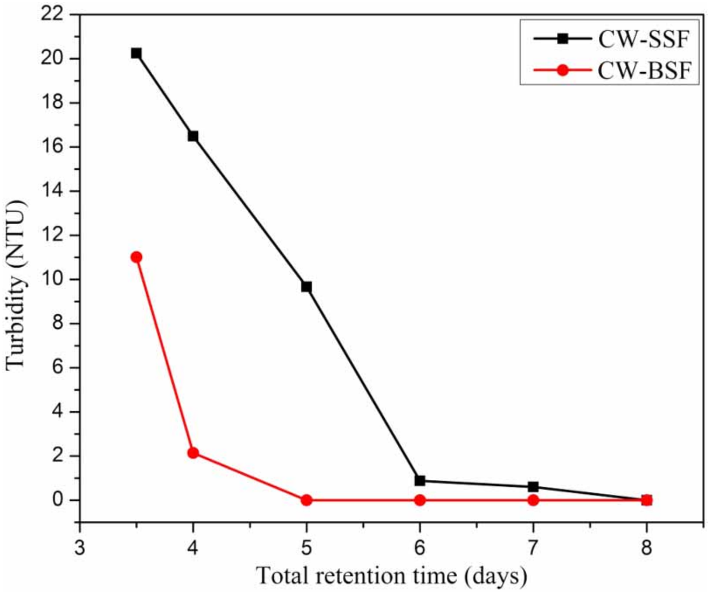

Figure 10 | Comparison of the variation of turbidity in the effluent of CW-SSF and CW-BSF with total retention time.

FC effluent

Figure 11 illustrates the final FC effluent from CW-SSF and CW-BSF as a function of total retention time where CW-BSF had better effluent than CW-SSF. It can be seen that CW-BSF and CW-SSF needed a total retention time of 5 and 7 days, respectively to produce effluent with 0 CFU/100 ml that fall within WHO and TBS drinking water standards. The good performance of CW-BSF over CW-SSF might be attributed to more contact time of raw water in BSF filter media caused by intermittent feeding mode and small sand size that allowed low infiltration rate as compared to SSF.

COD effluent

Figure 12 show clearly that CW-BSF had a better performance on COD removal compared to CW-SSF. Total retention time of 4 days for CW-BSF and 5 days for CW-SSF were needed to produce COD effluent of <10 mg/L, this is the COD concentration accepted by WHO standards for drinking

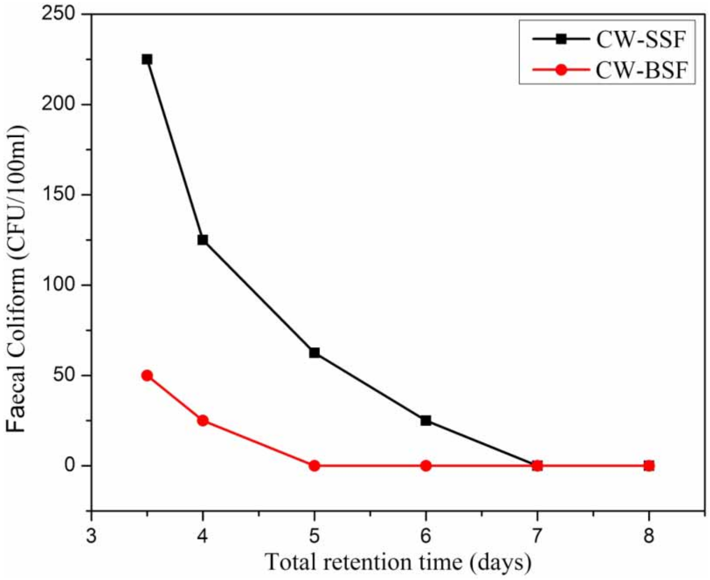

Figure 11 | Comparison of the variation of FC in the effluent of CW-SSF and CW-BSF with total retention time.

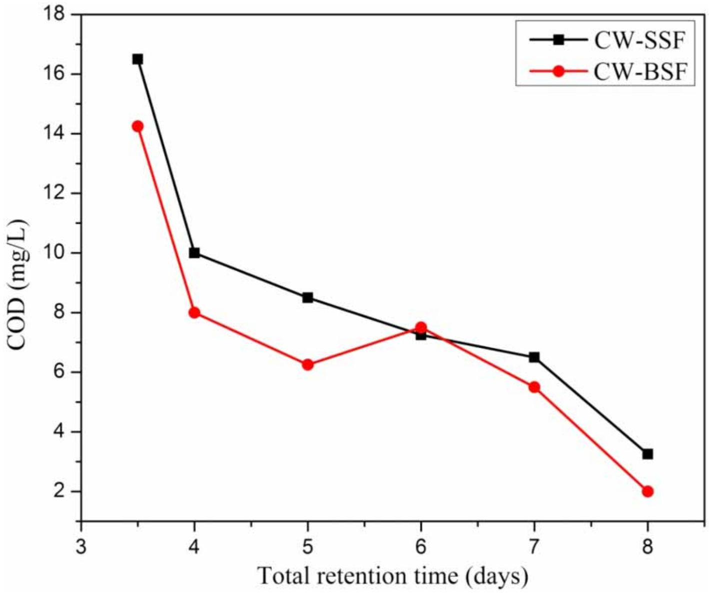

Figure 12 | Comparison of variation of COD in the effluent of CW-SSF and CW-BSF with total retention time.

water. The reason to better performance of CW-BSF compared to CW-SSF may be due to long holding and contact time of raw water in the sand media caused by batch feeding mode in BSF.

TSS effluent

The final TSS levels in the effluents of the integrated CW-SSF and CW-BSF as a function of total retention time is shown in Figure 13. It was observed that CW-BSF needed a total retention time of 4 days while CW-SSF needed 6 days to produce TSS effluent of <5 mg/L, a value accepted by WHO standard for drinking water. Better performance of CW-BSF over CW-SSF on TSS removal might be attributed to long contact time, small sand size and long sand column in BSF.

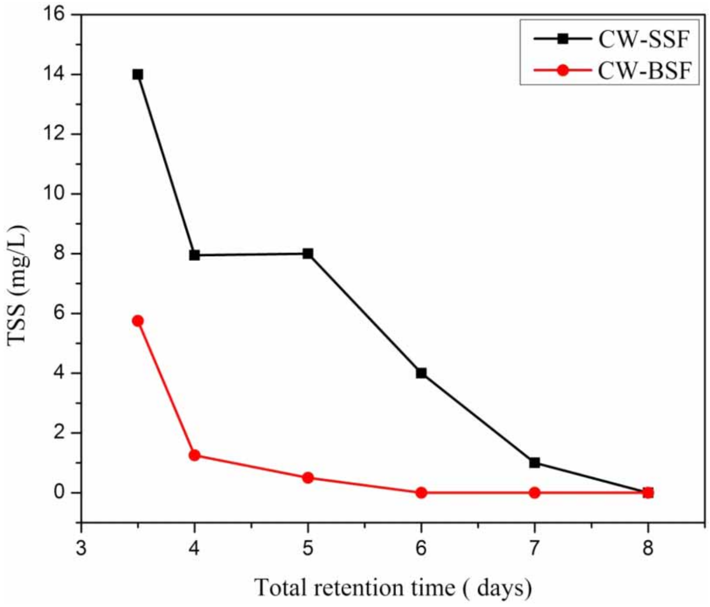

Figure 13 | Comparison of the variation of TSS in the effluent of CW-SSF and CW-BSF with total retention time.

Nitrate effluent

It is clear seen from the Figure 14 that integrated systems of CW-BSF and CW-SSF present good nitrate removal, whereby after a total retention time of 4 days nitrate concentration was less than 10 mg/L. However, CW-BSF had better quality of nitrate effluent with average value of 4.31 mg/L compared to 4.83 mg/L produced by CW-SSF. The removal of nitrate in sand filters was attributed to denitrification and sedimentation process within the sand column.

CONCLUSION

Treatment of high turbid water for drinking by constructed wetland integrated with sand filters proved to be feasible. It was observed that CW-BSF and CW-SSF systems were capable of producing an

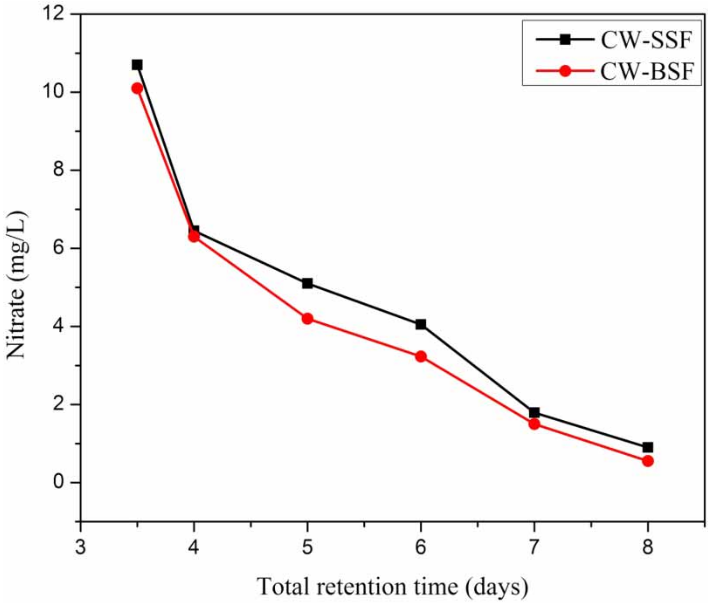

Figure 14 | Comparison of nitrate in the effluent of CW-SSF and CW-BSF with total retention time.

effluent quality that meets WHO and TBS standards for drinking water. CW-BSF needed an operational total retention time of 5 days to produce effluent of 0 NTU for turbidity, 0 CFU/100 ml for FC, 6.25 mg/L for COD, 0.5 mg/L for TSS and 4.2 mg/L for nitrate whereas, CW-SSF needed a total retention time of 7 days to produce effluent of 0.6 NTU for turbidity, 0 CFU/100 ml for FC, 6.5 mg/L for COD, 1 mg/L for TSS and 1.79 mg/L for nitrate. The allowable limits for drinking water standards according to WHO and TBS are 5–25 NTU for turbidity, 0 CFU/100 ml for FC, 10 mg/L for COD, 5 mg/L for TSS and 50 mg/L for nitrate. Therefore, this study reveal that CW-BSF shows better performance in treating high turbid water and qualify to be a potential low-cost, feasible and viable technology in providing potable water to under-served communities.

RECOMMENDATIONS

(i) Further study should be undertaken to validate the efficiency of this technology in protozoa and virus removal from drinking water.
(ii) The study recommends the scaling up and application of this technology to real environment where treatment of turbid water is challenging.

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CONFLICT OF INTEREST

No conflict of interest was declared.

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