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Filter Media Depth and Its Effect on the Efficiency of Household Slow Sand Filter in Continuous Flow

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This study evaluated the impact of a 50% reduction of filter media depth in Household Slow Sand Filters (HSSFs) on continuous flow to remove physicochemical and microbiological parameters from river water. Furthermore, simple pre-treatment and disinfection processes were evaluated as additional treatments. Two filter models with different filtration layer depths were evaluated: a traditional one with 50 cm media depth (T-HSSF) and a compact one (C-HSSF) with 25 cm. HSSFs were fed with pre-treated river water (24-h water sedimentation followed by synthetic fabric filtration) for 436 days at a constant filtration rate of 0.90 m^3 m^{-2} day^{-1} with a daily production of 48 L day^{-1}. Sodium hypochlorite (2.0 mg L^{-1} of NaOCl 2.5% for 30 min) was used to disinfect the filtered water. Water samples were analyzed weekly for parameters such as turbidity, organic matter, colour and *E. coli*, among others. Removal of protozoan cysts and oocysts by the HSSFs were also evaluated. After pretreatment, turbidity from the HSSF river water was reduced to 13.2 ± 14.6 NTU, allowing the filters to operate. Statistical analysis indicated no significant difference ($p > 0.05$) between T-HSSF and C-HSSF efficiencies in all evaluated parameters throughout operation time. Hence, media depth reduction did not hinder continuous HSSF performance for almost all the evaluated parameters. However, it may have affected *Giardia* cysts retaining, which passed through the thinner media on one evaluation day. Disinfection was effective in reducing remaining bacteria from filtered water; however, it was ineffective to inactivate protozoa. The reduction in the filtration layer did not affect the overall filtered water quality or quantity showing that a compact HSSF model may be a viable option for decentralized water treatment.

Keywords: biosand filter, decentralised treatment, drinking water, fine sand, river water

Abbreviations:

HWTS: Household Water Treatment and Safe Storage

HSSF: Household Slow Sand Filter

T-HSSF: Traditional Household Slow Sand Filter

C-HSSF: Compact Household Slow Sand Filter

1 Introduction

According to the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), 884 million people lacked basic drinking water services and 159 million used surface water as direct supply sources (WHO; UNICEF, 2017). In 2014, the ingestion of unsafe drinking water contributed to more than 502 thousand diarrhoea deaths, the majority being in vulnerable populations in Africa and South-East Asia (WHO, 2014).

Household water treatment and safe storage (HWTS) is an option for improving safe water and reducing disease in isolated communities. Among the available alternatives, the Household Slow Sand Filter (HSSF), a reduced scale slow sand filter with the most widespread model which is the Biosand filter (BSF), is one of the most promising. HSSF is efficient removing pathogens, such as bacteria and protozoa (Adeyemo et al., 2015; Terin and Sabogal-Paz, 2019; Young-Rojanschi and Madramootoo, 2014), in addition to have low-cost and be easy to use, with simple operation and maintenance (Andreoli and Sabogal-Paz, 2020).

HSSF is an adaptation of traditional slow sand filter on a home-scale operated in continuous flow or intermittent flow. Water purification in HSSFs occurs through a combination of physical-chemical processes along the sand filter bed and biological processes in the *Schtmuzdecke* layer formed at the bed top, which comprises organic matter (*e.g.,* microorganisms), manganese, iron and extracellular polymeric substances (EPS) (Ranjam and Prem, 2018).

Similar to any other slow sand filter, HSSF has reduced efficiency in the removal of chemical compounds, such as dissolved organic matter, and in the removal of water solids with high turbidity, as a high concentration of material suspended in the influent water obstructs the intergranular voids, causing a reduction in the functioning of the filter and an increase in the frequency of cleaning (Souza Freitas and Sabogal-Paz, 2019). Based on this, the maximum turbidity recommended for influent water is 50 NTU (CAWST, 2012); however, Sabogal-Paz et al. (2020) highlighted that this value must be reduced to 10 NTU in countries with restrictive drinking water standards. In cases of water with turbidity above that recommended, such as river water, CAWST (2012) suggests a pre-treatment by sedimentation so that the HSSF can function properly. Cloth filtration is another low-cost alternative able to reduce water turbidity (Siwila and Brink, 2019).

As with other treatment technologies, HSSF also requires a post-treatment step to reduce the microbiological risk that still exists in filtered water, especially during vulnerable periods, such as those preceding the formation of *Schmutzdecke*. Even though the HSSF has a reduced efficiency before the *Schmutzdecke* matures, when there is a lack of access to drinking water, improved water (i.e., with some treatment) is better for the user's health than water without any treatment. In this critical period of maturation, HSSF can improve the water quality and a post-treatment can make filtered water safer. Chlorine is a disinfectant that has been used for many years, hence, given the amount of evidence, there is a consensus of its benefits in significantly reducing the number of viable microorganisms and the risk of spreading diseases; additionally, the residual concentration of chlorine in disinfected water can prevent recurrent HSSF recontamination events (Stauber et al., 2012).

Although the initial HSSF model was designed for intermittent operation (Manz, 2004), the constant and lower filtration rate of continuous HSSFs provided conditions for a more stable *Schmutzdecke* development and higher turbidity and pathogen removal efficiencies (Young-Rojanschi and Madramootoo, 2014; Andreoli and Sabogal-Paz, 2020). According to Maciel and Sabogal-Paz (2020), water level control and a non-woven blanket at the filter media top are HSSF modifications that also contributed to the *Schmutzdecke* development and improved performance.

To transfer the technology to isolated communities, the HSSF structure must be adapted to the users' reality. Current HSSF models, which are 1 m high and weigh about 100 kg (Andreoli and Sabogal-Paz, 2020). Due to its size and weight, HSSF had to be placed on the floor and can occupy a considerable area within a residence, especially when allocated indoors, which is more suitable for their preservation and handling. Furthermore, cement HSSFs, although robust, require a complex set of tools to assemble. They can present cracks if constructed incorrectly and are more difficult to transport than plastic HSSFs (Sisson et al., 2013; Vanderzwaag et al., 2009). This scenario motivates studies that evaluate the ability to operate filters with a reduced filter bed thickness to make them smaller, lighter and liable to be placed on a kitchen countertop.

Studies that assessed the impact of reducing the filter bed depth were started with intermittent HSSF (Adeyemo et al., 2015; Hussain et al., 2015; Mwabi et al., 2012; Mahlangu et al., 2012; Mwabi et al., 2013; Napotnik et al., 2017; Napotnik et al., 2020). All mentioned studies proposed HSSFs constructed inside buckets, with media depths of 10 to 15 cm. Compact intermittent HSSFs presented the potential to remove turbidity (up to 98%), pathogens (up to 4.8 log removal of *Cryptosporidium parvum* and *Vibrio cholerae*), indicators of faecal contamination (up to 4.4 log removal of E. *coli*) and chemical compounds (removal rates of 93% for calcium, 54% for magnesium, 73% for iron, 55% for arsenic and 18% for nitrites). However, such models produced a reduced filtered water volume due to the unit's void volumes. This considerable disadvantage could be circumvented in a continuous HSSF since this regime maintains the filtration rate and daily production regardless of the volume of voids; while intermittent HSSFs require being fed several times to keep the required daily production.

Considering that there is no similar study published in the peer-reviewed literature about compact continuous HSSF, this study evaluated the impact of reduced filter media depth in continuous HSSF performance to remove physicochemical and microbiological parameters from river water. The experiments were conducted in a long-term operation (436 days) in order to fully assess the quality and quantity of filtered water caused by the reduction of the filter bed. Additionally, this study evaluated the reduction of river water turbidity by a simple pre-treatment by sedimentation and passage through blankets and the reduction of microbiological risk by post-treatment with sodium hypochlorite. Furthermore, the study expanded the knowledge regarding protozoa removal by HSSF, a topic rarely addressed in the literature.

2 Materials and methods

2.1 Proposed Household Water Treatment

Household water treatment for river water (Figure 1) was operated for 436 continuous days (from 17th May 2018 to 25th July 2019). The operation time included periods of the dry season (May to July 2018 and April to July 2019) and the rainy season (August 2018 to March 2019), according to the São Carlos (Brazil) Station meteorological database at the National Institute of Meteorology.

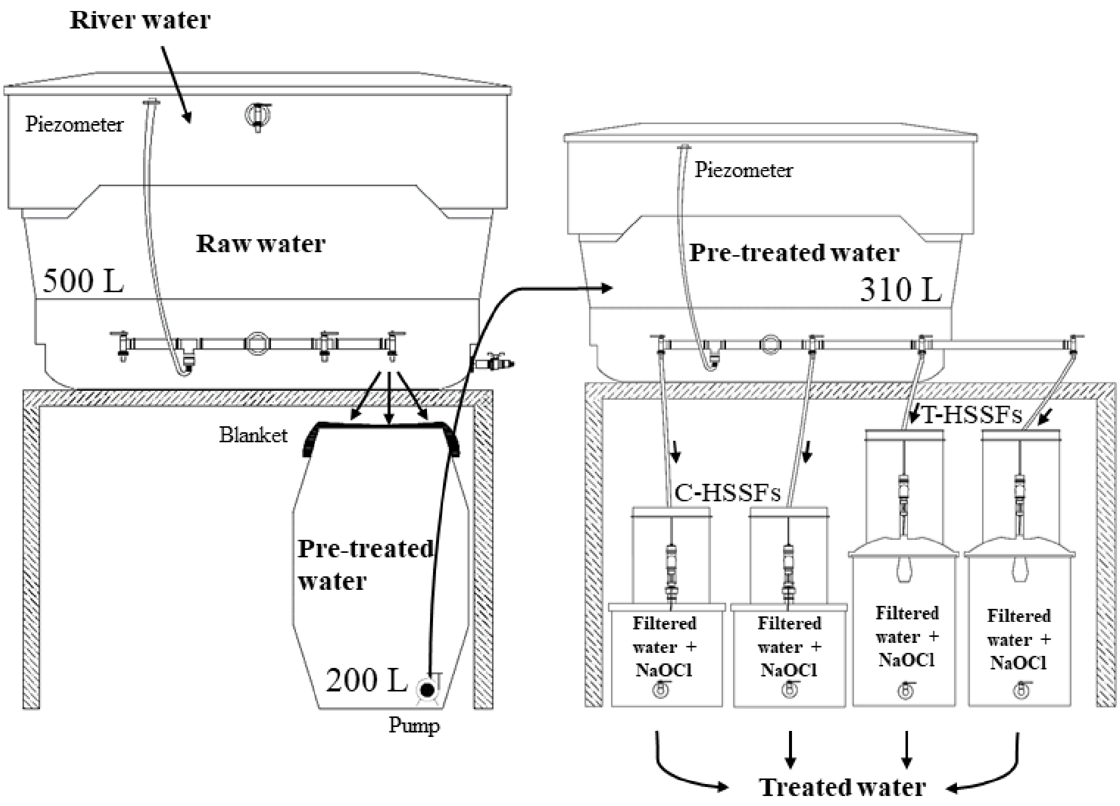

Figure 1. Complete river water treatment studied

2.2 River water and pre-treatment

Daily, river water from Monjolinho River (São Carlos/Brazil) was pumped to a 500 L elevated reservoir and maintained for 24 h for sedimentation. After this period, the tap installed in the reservoir was opened and water passed through two layers of non-woven synthetic fabric (the same blanket used on HSSF). A 200 L reservoir stored the pre-treated water that resulted from this first stage of household water treatment. Remaining water from the 500 L elevated reservoir was discarded and the reservoir was filled with new river water to restart the pre-treatment for the next day.

2.3 Household slow sand filters

2.3.1 Structure

Four HSSFs were constructed with fittings and PVC pipes (cross-sectional area = 0.053 m^2), using the Terin and Sabogal-Paz (2019) prototype as a base model. Two filters with the traditional model (T-HSSF) and two filters with the compact model (C-HSSF) were studied. T-HSSF and C-HSSF differed in the fine sand layer depth (50 cm and 25 cm, respectively) and in their total height (T-HSSF had 90 cm and C-HSSF had 65 cm). Both models are shown in Figure 2.

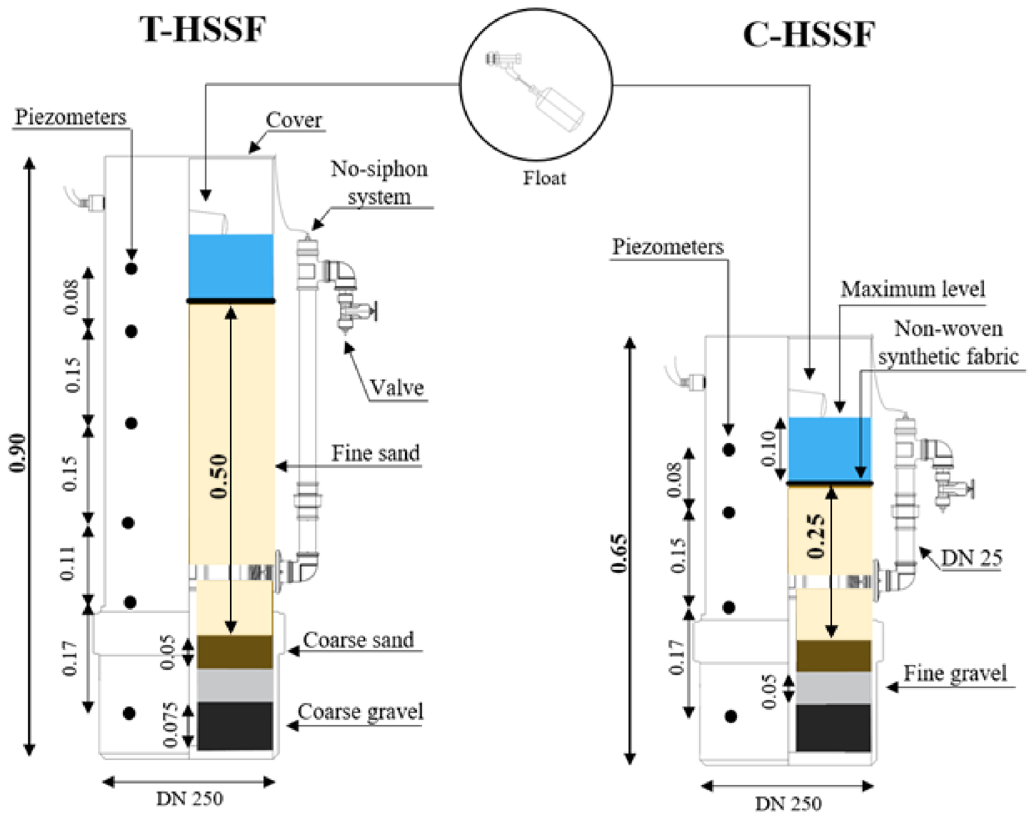

Figure 2. Cross-section of the two HSSF models (T-HSSF: traditional model and C-HSSF: compact model), units in meters.

The fine sand used as a media had a grain size of 0.17 to 0.56 mm, an effective size (D_{10}) of 0.17 mm, a uniformity coefficient (UC) of 2.27 and a porosity of 37%. Support media was the same for the four HSSFs, and consisted of a 5 cm layer of coarse sand (0.17 to 0.67 mm), a 5 cm layer of fine gravel (5 to 7 mm) and a 7.5 cm layer of coarse gravel (7 to 12 mm). All materials were washed, sun-dried and sieved using commercial sieves that were easily accessible (i.e. sieves used to select rice, beans, flour, etc.). A non-woven synthetic fabric (2.0 mm of thickness, 0.2 g cm^{-3} of specific mass, 100% polyester) was positioned at the filter media top and fixed by a PVC ring.

2.3.2 Operation

Daily, 200 L of pre-treated water was pumped to a 310 L elevated reservoir used to feed the filters. HSSFs were designed to be operated in a continuous flow with a constant water level. The filtration rate was kept constant (0.90 m^3 m^{-2} day^{-1}) by a needle valve faucet at the filter outlet and the water level inside the filter (10 cm) was kept by a float valve (Figure 2). The household slow sand filtration was the second stage of water treatment. Each HSSF produced 48 L day^{-1}, which could provide the minimum acceptable for consumption and food preparation for 6 people (7.5 L hab^{-1} day^{-1}) (Howard and Bartram, 2003).

After the 330th day, the HSSFs were overloaded with *Giardia* spp. cysts and *Cryptosporidium* spp. oocysts from purified suspensions (Waterborne® Inc, USA). Approximately 10^3 cysts and 10^2 oocysts were added daily to the HSSF inlets to assess the household water treatment performance, simulating sources with a protozoa risk.

2.3.3 Maintenance

The filtration rate decreased over time due to particle accumulation and biological layer development. Therefore, the flow rate was adjusted daily by regulating the faucet on the outlet filter to maintain the production of 48 L day^{-1}. HSSFs were cleaned when they were not able to keep the production even with the valve fully open. In addition, the maturation time and filter run of the two filter models were compared.

The maintenance was carried out as follows: the needle valve faucet was closed and the synthetic fabric was removed. The sand top layer was suspended by manual mixing and the supernatant was drained after sand sedimentation. Finally, the fabric was scraped, washed and repositioned at the sand top layer. The flow rate was adjusted to restart the operation.

2.4 Disinfection

To provide safe water, reduce the microbiological load and avoid recontamination of filtered water, the third stage of the household treatment was disinfection by sodium hypochlorite (NaOCl). Reservoirs positioned in front of each HSSF were used for disinfection (different reservoir models were used to fit under their respective filter). Disinfection was made by mixing a volume of commercial sodium hypochlorite (10-12%) diluted to 2.5% in 48 L filtered water with a spoon. The optimum point for disinfecting filtered waters was determined in laboratory tests (Figure S1, supplementary material). The NaOCl dosage of 1.0 mg L^{-1} for 30 min of contact time (1.87 mL of 2.5% NaOCl) guaranteed the free residual chlorine of 0.5 mg L^{-1} (WHO, 1985) and, therefore, was selected for the post-treatment of HSSFs. However, after a few days, total coliform tests demonstrated that this optimum point was insufficient to completely inactivate the bacteria in the filtered water on a household scale. For this reason, the dosage was increased to 2.0 mg L^{-1} (3.74 mL of 2.5% NaOCl) maintaining the contact time at 30 min, as recommended by WHO (2017) for home chlorine disinfection for waters with turbidity values below 10 NTU.

2.5 Tracer tests

Tracer tests were conducted identically to the filters' operation (constant filtration rate = 0.90 m^3 m^{-2} day^{-1}) to characterise C-HSSF and T-HSSF flow patterns. A 100 mg L^{-1} NaCl solution was added to the filter supply reservoir and used as a step injection tracer. The tracer was measured at the filter outlet with a conductivity probe (with *Go!Link* interface) and registered by *Logger Lite* software (Vernier Software & Technology, EUA). The data collected by the probe resulted in tracer concentration over time curves (*C x t*). Tracer tests were performed in triplicate for each filter.

Data processing followed the methodology proposed by Levenspiel (1999), starting by the normalisation of *C x t* curve in Excel® (*Microsoft*, EUA). Differentiation of the F curve in Origin 8.6® (*OriginLab*, EUA) resulted in a Residence Time Distribution (DTR) curve, an important curve for obtaining the sample collection time for each filter through the Hydraulic Retention Time (HRT). Information about flow behaviour (complete mixing or plug flow) was analysed by adjusting the DTR curves into three hydrodynamic mathematical models: low dispersion, high dispersion, and N-continuous stirred tank reactors (N-CSTR).

2.6 Sample collection and analysis

River water, pre-treated water, filtered water, and treated water samples were collected and analysed on weekdays according to the sample collection time defined by the tracer tests. All the samples were stored in an air-conditioned environment and analysed on the day following the collection.

Water samples were analysed in terms of turbidity (2100N Turbidimeter - *Hach Company*, USA), apparent and true colour (DM-COR Colorimeter - *Digimed*, Brazil), pH and total alkalinity (DM20 pH meter - *Digimed*, Brazil), total organic carbon

(TOC-L - *Shimadzu*, Japan), absorbance (λ = 254 nm) (DR5000 spectrophotometer - *Hach Company*, USA), electrical conductivity (DM32 conductivity meter - *Digimed*, Brazil), dissolved oxygen (DO 5519 – *Lutron*, Brazil), total coliforms and *Escherichia coli* (9222 Membrane filter technique for members of the coliform group - APHA et al. (2012)), particle size (Zetasizer - *Malvern*, United Kingdom).

Filtered water and treated water were also evaluated regarding *Giardia* spp. cysts and *Cryptosporidium* spp. oocysts six times in point analyses (344th, 365th, 379th, 388th, 423rd and 431st day of operation). HSSF daily production was divided into two 24 L samples, of which only one was disinfected by sodium hypochlorite. Results were used to assess the filter performance by itself and its combination with disinfection.

Protozoa samples were concentrated by filtration of the 24 L samples with cellulose mixed ester membranes (Ø 47 mm and 3 µm nominal porosity, Millipore®) according to Franco et al. (2016). Detection was performed by immunofluorescence assay (IFA) using the Merifluor® kit (Meridian Bioscience Diagnostics, USA), following the manufacturer's protocol and Method 1623.1 (USEPA, 2012). Samples were examined using an epifluorescence microscope (Olympus® BX51, Japan). Only organisms compliant with USEPA (2012) in terms of size, morphology, shape and fluorescence were considered. Analytical quality assays with ColorSeed® (TCS Bioscience, United Kingdom) using the same detection method were performed to verify if the matrix would influence the protozoa recovery. The protozoa viability in filtered and treated water samples was also estimated by the membrane permeability using propidium iodide (PI) as a vital dye (Silva and Sabogal-Paz, 2020).

Piezometers disposed at different depths (Figure 1) were used to evaluate the impurity retention progress and the head loss throughout the operation time. For comparative purposes, the piezometers were positioned at similar depths in both HSSF models (Figure 1).

2.7 *Schmutzdecke* evaluation

Schmutzdecke samples from fabric and sand's first millimetres were evaluated at the end of the HSSFs operation. The scraped material in the last maintenance was quantified, in triplicate, in volatile suspended solids (APHA et al., 2012) and concentrated by triple centrifugation (1000xg) to visualize the microorganisms. A drop of the concentrated sample was visualised by bright field microscopy under a microscope (Olympus® BX60, Japan) at 10x to 800x magnification. No dyes were used to stain the samples, therefore microorganisms that require staining were not visualised by microscopy (*e.g.,* bacteria and *Cryptosporidium* oocysts).

Furthermore, Scanning Electron Microscope (SEM) (Zeiss® LEO 440, Germany) was used to capture fabric photomicrographs before and after the filter operation to visualise how particles and microorganisms were adhered to fabric fibres.

2.8 Statistical analyses

Statistical analyses were performed on PAST 3.25 software (PAlaeontological STatistics). Datasets obtained were evaluated according to the normal distribution by the Shapiro-Wilk test. Normal distribution datasets were compared by the Student's t-test (independent) or Student's t-test paired (dependent), while non-normal datasets were compared by the Mann-Whitney U test (independent) or Wilcoxon test (dependent). All tests compared datasets as pairwise to determine if there was a significant ($p < 0.05$) difference between them.

Bivariate analyses investigated the correlation between the filters' performance (turbidity, total coliforms and *E. coli* of filtered water) and operating parameters (operating time, time after maintenance, and turbidity, total coliforms and *E. coli* of pre-treated water). Spearman's correlation was applied to these analyses, since all datasets had non-normal distribution. A significant correlation was defined as having both $p < 0.05$ and $|r|$ greater than r-critical.

3 Results and discussion

3.1 HSSF construction

T-HSSF had a structural weight of 12.4 kg and C-HSSF had 10.3 kg. Although the difference in weight was small, when including granular materials and water from granular voids, this difference became significant. T-HSSF was filled with 44.4 kg of fine sand, 18.5 kg of granular materials, and 19.6 kg of water in granular voids, while the C-HSSF had 22.2 kg of fine sand, 18.5 kg of granular materials, and 14.5 kg of water. Thus, the T-HSSF ready for operation had 94.9 kg weight and C-HSSF had 65.5 kg. The 50% reduction in the filter bed proposed by the compact model reduced the weight by 31% and the height by 28% (90 cm versus 65 cm), when compared to the base model (T-HSSF). These improvements can be substantial for technology transfer as it helps users to handle and transport the structure.

3.2 Tracer tests

Tracer test results for T-HSSF and C-HSSF are shown in Table 1. HRT was used as the sample collection time for each filter, which was lower in C-HSSF than in T-HSSF due to the reduction of bed depth and pore volume.

In most cases, the high dispersion model showed the greatest correlation with the experimental curves (Table 1). Uni-parametric measurements (D uL^{-1}) of this model demonstrate that the T-HSSF has lower dispersions and a flow regime nearer to an ideal plug-flow than the C-HSSF. From the perspective of the biological layer development and microbial removal processes, this difference between flow regimes may favour the T-HSSF, as reported by Sabogal-Paz et al., (2020).

Table 1. Tracer tests results for the traditional model (T-HSSF) and compact model (C-HSSF)

Filter		T-HSSF		C-HSSF	
Replica		1	2	1	2
HRT (min)		560 ± 17	566 ± 30	426 ± 7	427 ± 6
N-CSTR	N	10 ± 1	13 ± 0	6 ± 1	7 ± 1
	|r|	0.81 ± 0.03	0.78 ± 0.03	0.76 ± 0.05	0.81 ± 0.02
Low dispersion model	D/uL	0.053 ± 0.005	0.038 ± 0.001	0.083 ± 0.013	0.070 ± 0.009
	|r|	0.73 ± 0.02	0.72 ± 0.02	0.71 ± 0.03	0.74 ± 0.02
High dispersion model	D/uL	0.045 ± 0.004	0.034 ± 0.000	0.066 ± 0.009	0.057 ± 0.006
	|r|	0.80 ± 0.07	0.84 ± 0.04	0.84 ± 0.02	0.85 ± 0.02

Notes: HRT: hydraulic retention time; N-CSTR: N-continuous stirred tank reactors model; N: number of stirred tank reactors; D/uL: dimensionless group characterising the spread in the whole reactor; and |r|: Spearman correlation

3.3 Pre-treatment performance

Water quality parameters for river water and pre-treated water, as well as the pre-treatment efficiency are in Table 2. The pre-treatment was able to reduce 46 ± 23% of turbidity and achieved 13.2 ± 14.6 NTU. Pre-treated water showed turbidity above 10 NTU in 35% of the samples, and was only 4% above 50 NTU, which is the maximum recommended by CAWST (2012).

Table 2. Water quality for river water and pre-treated water and pre-treatment efficiency

Parameter	River water	Pre-treated water	Removal (R) or variation (V)	p-value
	Mean ± Standard Deviation			
Turbidity (NTU)	26.5 ± 25.6	13.2 ± 14.6	46 ± 23 % (R)	< **0.01**
Apparent colour (UH)	79.3 ± 54.9	61.4 ± 43.2	21 ± 19 % (R)	< **0.01**
True colour (UH)	32.6 ± 23.7	31.4 ± 21.8	0.2 ± 26 % (R)	**0.04**
pH	6.93 ± 0.14	7.05 ± 0.10	- 1.73 ± 2.08 % (V)	< **0.01**
Total organic carbon (mg L^{-1})	2.47 ± 0.78	2.07 ± 0.87	13 ± 30 % (R)	< **0.01**

Total alkalinity ($mgCaCO_3$ L^{-1})	18.8 ± 2.3	20.2 ± 6.7	- 8.8 ± 39 % (V)	0.94
Absorbance (λ = 254 nm)	0.111 ± 0.064	0.109 ± 0.061	1.2 ± 21 % (R)	0.59
Electrical conductivity (μS cm^{-1})	49.11 ± 7.54	48.60 ± 6.70	0.8 ± 4.2 % (V)	0.22
Dissolved oxygen (mg L^{-1})	7.7 ± 0.5	7.8 ± 0.4	- 2.2 ± 6.5 % (V)	**0.03**
Particle size (nm)	476.1 ± 269.1	301.3 ± 87.3	29 ± 27 % (R)	< **0.01**
Total coliforms (CFU (100 mL^{-1}))	3.97 ± 3.75 log	3.73 ± 3.63 log	0.27 ± 0.31 log (R)	< **0.01**
Escherichia coli (CFU (100 mL^{-1}))	2.98 ± 3.11 log	2.52 ± 2.71 log	0.39 ± 0.35 log (R)	< **0.01**
Notes: $p < 0.05$ was considered statistically significant				

Differences between the seasons were observed on pre-treated water quality, once turbidity on river water was higher in the rainy season than the dry season (33.74 ± 29.36 NTU versus 18.94 ± 18.04 NTU). It is noteworthy that the pre-treatment was not able to maintain the same water quality during the operation time (17.50 ± 17.19 NTU in the rainy season versus 8.24 ± 8.55 NTU in the dry season).

The pre-treatment was designed to be accessible and low cost, without the need for coagulants, enabling the operation of the HSSF during the study period.

3.4 HSSF performance

The filtered water quality from T-HSSF and C-HSSF was presented as the average values. Filtered water and efficiency from both HSSF models are shown in Table 3.

Table 3. Quality of filtered non-disinfected water and efficiency of traditional model (T-HSFF) and compact model (C-HSSF)

Parameter	Pre-treated water	T-HSSF filtered water	C-HSSF filtered water
	Mean ± Standard Deviation		
Turbidity (NTU)	13.2 ± 14.6	3.13 ± 4.77	3.30 ± 5.24
Apparent colour (HU)	61.4 ± 43.6	16.1 ± 23.6	16.6 ± 20.6
True colour (HU)	31.4 ± 21.8	13.0 ± 19.0	12.9 ± 16.2
Absorbance (λ = 254 nm)	0.109 ± 0.061	0.054 ± 0.050	0.054 ± 0.045
pH	7.05 ± 0.10	7.18 ± 0.09	7.16 ± 0.10
Total alkalinity (mg$CaCO_3$ L^{-1})	20.2 ± 6.7	18.1 ± 1.6	18.5 ± 1.8
Total organic carbon (mg L^{-1})	2.07 ± 0.87	1.85 ± 0.50	1.95 ± 0.55
Electrical conductivity (µS cm^{-1})	48.60 ± 6.70	47.99 ± 6.77	48.36 ± 6.99
Dissolved oxygen (mg L^{-1})	7.8 ± 0.4	8.2 ± 0.4	8.1 ± 0.4

Particle size (nm)	301.3 ± 87.3	284.1 ± 123.4	256.0 ± 125.7
Total coliforms (CFU (100 mL^{-1}))	5356 ± 4302	42 ± 140	44 ± 148
Escherichia coli (CFU (100 mL^{-1}))	332 ± 511	4 ± 9	5 ± 11
Giardia cysts (cysts in 48 L^{-1})	1001 ± 264	Absence	2 ± 5
Cryptosporidium oocysts (oocysts in 48 L^{-1})	264 ± 169	15 ± 3	24 ± 15

Notes: p-values between filters' performance ranged from 0.15 to 0.97, so there were no significant differences between the models (p-values < 0.05)

According to the Mann-Whitney test, there was no significant difference ($p > 0.05$) between T-HSSF and C-HSSF performance in all evaluated parameters throughout the operation time (Table 3). The results showed that the filter performance was maintained even with a thinner filter media (25 cm), demonstrating the predominance of water treatment by surface action, just as occurs in conventional slow sand filtration.

Although the filtered water for true colour was below the limit value of 15 HU (WHO, 2017), 22% and 27% of the T-HSSF and C-HSSF samples, respectively, were not in compliance. These high values of remaining true colour were explained by the low efficiency of slow sand filtration in removing humic substances (Ellis and Wood, 1985). Absorbance measurements indicated an organic matter removal higher than that reported by Lynn et al. (2013) in an intermittent HSSF.

Increased pH of 1.6 to 1.8% was observed after filtration by both models. Murphy et al. (2010) noted a similar alteration; nevertheless, the authors attributed the increased pH to the calcium carbonate leaching from the filter walls made of concrete.

As in our study, the filters were built in PVC, the increase may have occurred due to the filter media leaching, according to Sabogal-Paz et al. (2020).

The TOC of the filtered water samples was practically equal to the TOC of the pre-treated water (around 2 mg L^{-1}). This low availability of nutrients from pre-treated water could have impaired the biological activity of HSSFs (Lynn et al., 2013); however, the operational conditions of the study allowed the development of *Schmutzdeckes* in both models.

Dissolved oxygen increased in both filtered water samples. Young-Rojanschi and Madramootoo (2014) also noted an increase; however, the authors firstly observed DO consumption along the filter media length caused by *Schmutzdecke* and then a reaeration in the outlet pipe. Therefore, increased DO measures in the filtered water may be a reaeration consequence and not an absence of *Schmutzdecke* growth.

As the average particle size in the pre-treated water (301.3 ± 87.3 nm) had the size for the predominant action of Brownian movement (Parsons and Jefferson, 2006), only a slight reduction in the particle size was observed in both filtered water samples.

The impact of filter media depth reduction was also analysed considering the HSSFs performance during the dry and rainy seasons. In this case, the HSSF model impact during the same season and the seasonality on each HSSF model were evaluated (Table 4).

Table 4. Statistical analysis to compare the HSSF model effect and season effect for different parameters

Parameter	HSSF model effect		Season effect	
	Dry season	Rainy season	T-HSSF	C-HSSF

Turbidity (NTU)	0.68	0.70	**0.02**	0.12
Apparent colour (UH)	0.99	0.14	0.24	0.76
True colour (UH)	0.97	0.77	0.77	0.81
pH	0.54	0.72	**0.04**	0.07
Total organic carbon (mg L^{-1})	0.49	0.48	**0.03**	0.05
Total alkalinity (mg$CaCO_3$ L^{-1})	0.63	0.54	0.91	0.82
Absorbance (λ = 254 nm)	0.91	0.51	0.42	0.50
Electrical conductivity (µS cm^{-2})	0.49	0.71	0.07	0.08
Dissolved oxygen (mg L^{-1})	0.51	0.51	**< 0.01**	**< 0.01**
Particle size (nm)	0.44	0.94	0.58	0.23
Escherichia coli (CFU (100 mL^{-1}))	0.74	0.39	0.07	0.16
Total coliforms (CFU (100 mL^{-1}))	0.76	0.71	**< 0.01**	**< 0.01**

Notes: T-HSSF: traditional model; and C-HSSF: compact model; $p < 0.05$ was considered statically significant. *Giardia* cysts and *Cryptosporidium* oocysts were not evaluated.

During the same season, both filter models produced filtered water with no significant different quality ($p > 0.05$), which indicates that the reduced filter media did not influence the performance even in periods with higher influent turbidity, as seen in the rainy season. However, in different seasons the performance between both models was significantly different ($p < 0.05$) for some water quality parameters. The change of season affected the performance more than the HSSF model type. Therefore, the change of river water quality during the year was more relevant to the filtered water quality than the fine sand depth.

3.4.1 Head loss development

Filter run progress was observed by the retention of impurities in filter media, and consequently head loss development. For comparative purposes, the head loss was expressed as the difference between piezometers (Δh) divided by the thickness of filter media (L). The head loss at the filter media top and the total bed length of the two models are shown in Figure 3.

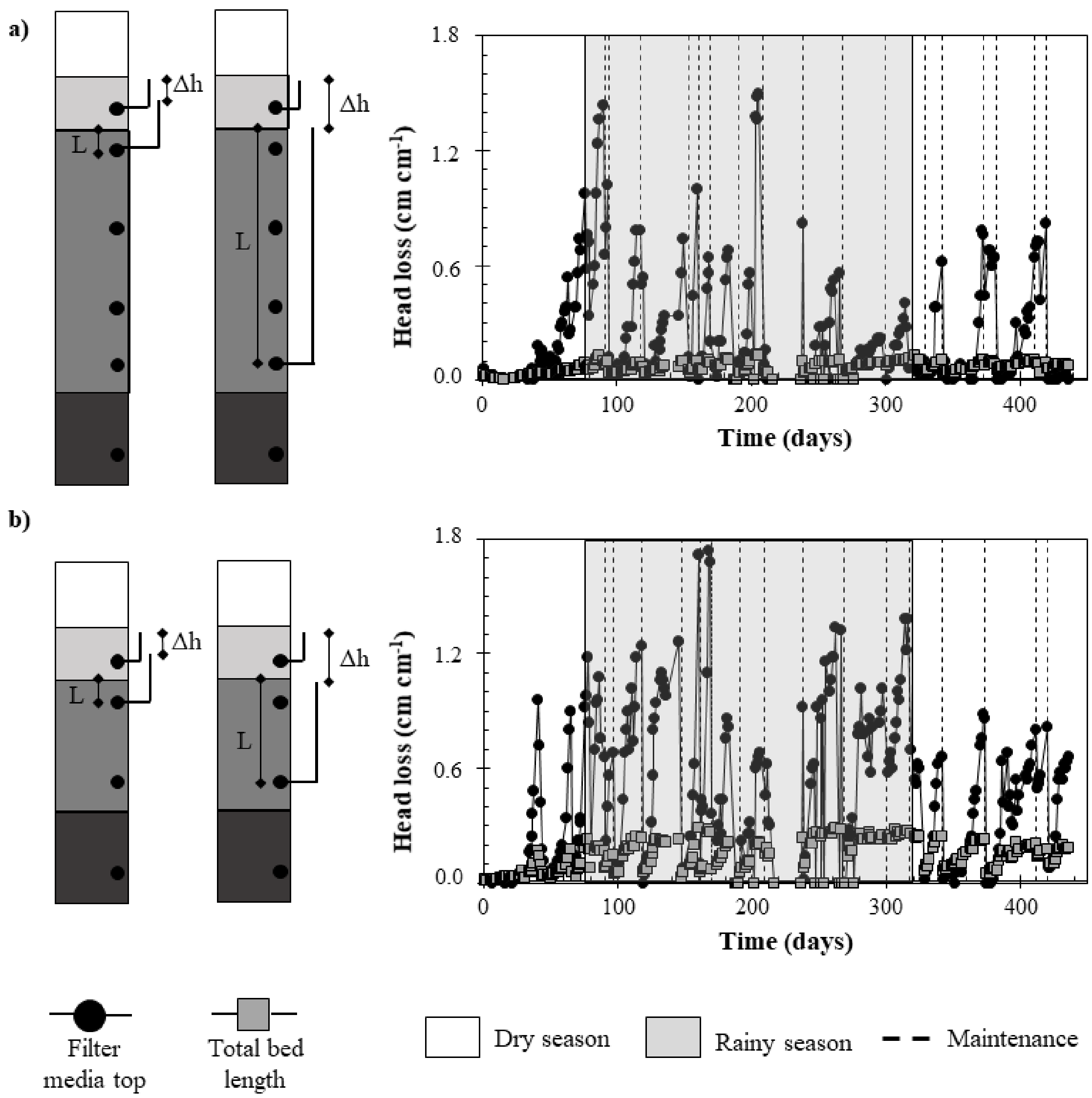

Figure 3. Head loss at the filter media top (Δh L^{-1} between the first and second piezometers) and at the total bed length (Δh L^{-1} between the first and penultimate piezometer) in HSSFs: a) traditional model (T-HSSF) and b) compact model (C-HSSF).

Both models operated for 91 days until the first maintenance; however, during the rainy season the need for maintenance became more frequent. Fifteen maintenances were required in each filter model over the operation time (Figure 3), reaching average filter runs of 28 ± 20 days in the T-HSSF and 29 ± 21 days in the C-HSSF. No significant difference in the filter run length was observed between the HSSF models ($p = 0.85$).

The filter runs obtained in our study were lower than the literature for continuous flows (Maciel and Sabogal-Paz, 2020; Souza Freitas and Sabogal-Paz, 2019; Andreoli and Sabogal-Paz, 2020). Factors such as the filtration rate, sand size, bed depth and influent water quality may explain the differences between the studies.

Impurity retention in both models occurred predominantly at the filter media top; an expected fact in slow sand filtration process due to the effective diameter of fine sand media (Maciel and Sabogal-Paz, 2020). Nevertheless, the head loss progress at the total bed length was different between the filter models. T-HSSF showed little change throughout the operation time (Figure 3a), while C-HSSF showed impurity retention along the filter runs (Figure 3b). The small head loss value at the total bed length in T-HSSF indicated that few particles were retained at the last centimetres of media, while C-HSSF had impurity retention at the whole bed depth. Head loss results suggest that a reduced filter media depth may be sufficient for impurity retention in HSSF, as well as demonstrated by the statistical similarity of the filter's performance (Table 3).

3.4.2 Turbidity removal

Turbidity from each filter model is shown in Figure 4. Turbidity removal of 73 ± 20% from T-HSSF and C-HSSF was lower than that observed in the studies that used influent water with similar turbidity (89.4% to 96.8%) (Maciel and Sabogal-Paz, 2020; Mwabi et al., 2013; Napotnik et al., 2017; Young-Rojanschi and Madramootoo, 2014).

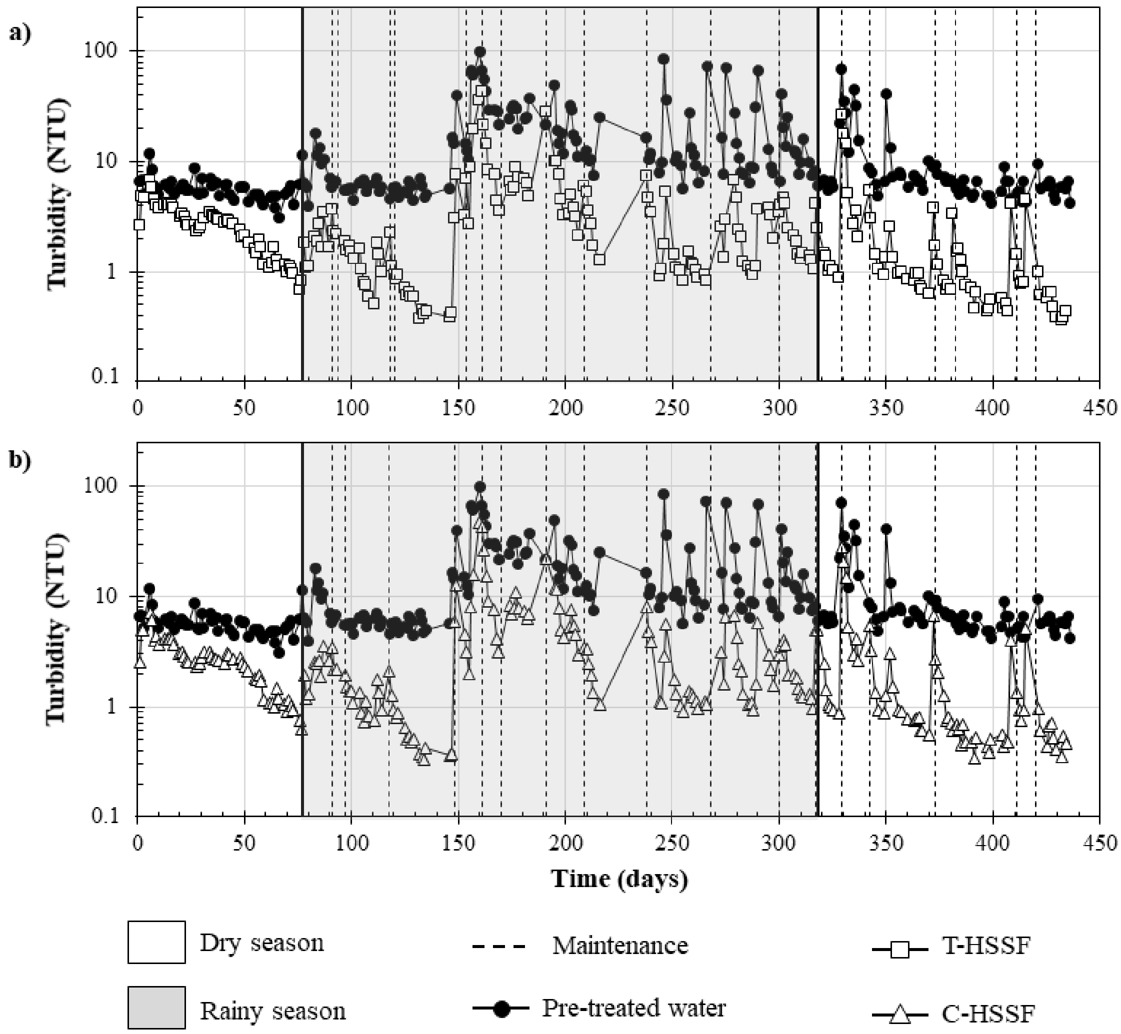

Figure 4. Turbidity values in the pre-treated water from the Monjolinho River and the average values in the filtered water from a) the traditional model: T-HSSF, and b) the compact model: C-HSSF.

A possible reason for the higher turbidity removal in the literature may be the reduced filtration rates applied to continuous filters with similar T-HSSF media length (Maciel and Sabogal-Paz, 2020; Young-Rojanschi and Madramootoo, 2014) and the reduced daily production by intermittent HSSFs with thinner media, analogous to those used by C-HSSF (Mwabi et al., 2013; Napotnik et al., 2017; Napotnik et al., 2020). Therefore, factors such as the operational flow, daily production and filtration rate play an important role for turbidity removal.

T-HSSF and C-HSSF produced water with turbidity below the maximum value of 5.0 NTU (WHO 2017) in 87% and 84% of the samples, respectively. Turbidity below 1.0 NTU (WHO, 2017) was achieved in 27% and 29% of the samples from T-HSSF and C-HSSF, respectively. Filtered water turbidity showed a strong correlation (Table S1, supplementary material) with influent water, operation time and time after maintenance (Spearman's correlation, $p < 0.001$).

Filtered water turbidity presented the highest correlation with pre-treated water turbidity for both T-HSSF and C-HSSF. This shows that the influent water quality is an important operational parameter for continuous filters, as well as for intermittent ones (Napotnik et al., 2020). The differences between seasons affected the filtered water turbidity. Influent water had turbidity of 8.24 ± 8.55 NTU during the dry season and 17.50 ± 17.19 NTU during the rainy season. During the dry season, the filtered water achieved 2.32 ± 3.10 NTU for T-HSSF and 2.36 ± 3.35 NTU for C-HSSF, while in the rainy season, the filtered water values increased to 3.91 ± 5.86 NTU in the T-HSSF and 4.21 ± 6.46 NTU in the C-HSSF.

Filtered water turbidity also correlated with operation time. T-HSSF and C-HSSF achieved lower levels of turbidity over time, as a consequence of the ripening process (Mwabi et al., 2012). At the beginning of the operation, the filters took almost 70 days to produce water with 1.0 NTU, whereas, in the end, this value was reached 2 days after maintenance. Increased performances regarding turbidity removal showed correlation with time after maintenance, as observed by Maciel and Sabogal-Paz (2020).

3.4.3 Bacteria reduction

E. coli reduction over time for each filter model is shown in Figure 5.

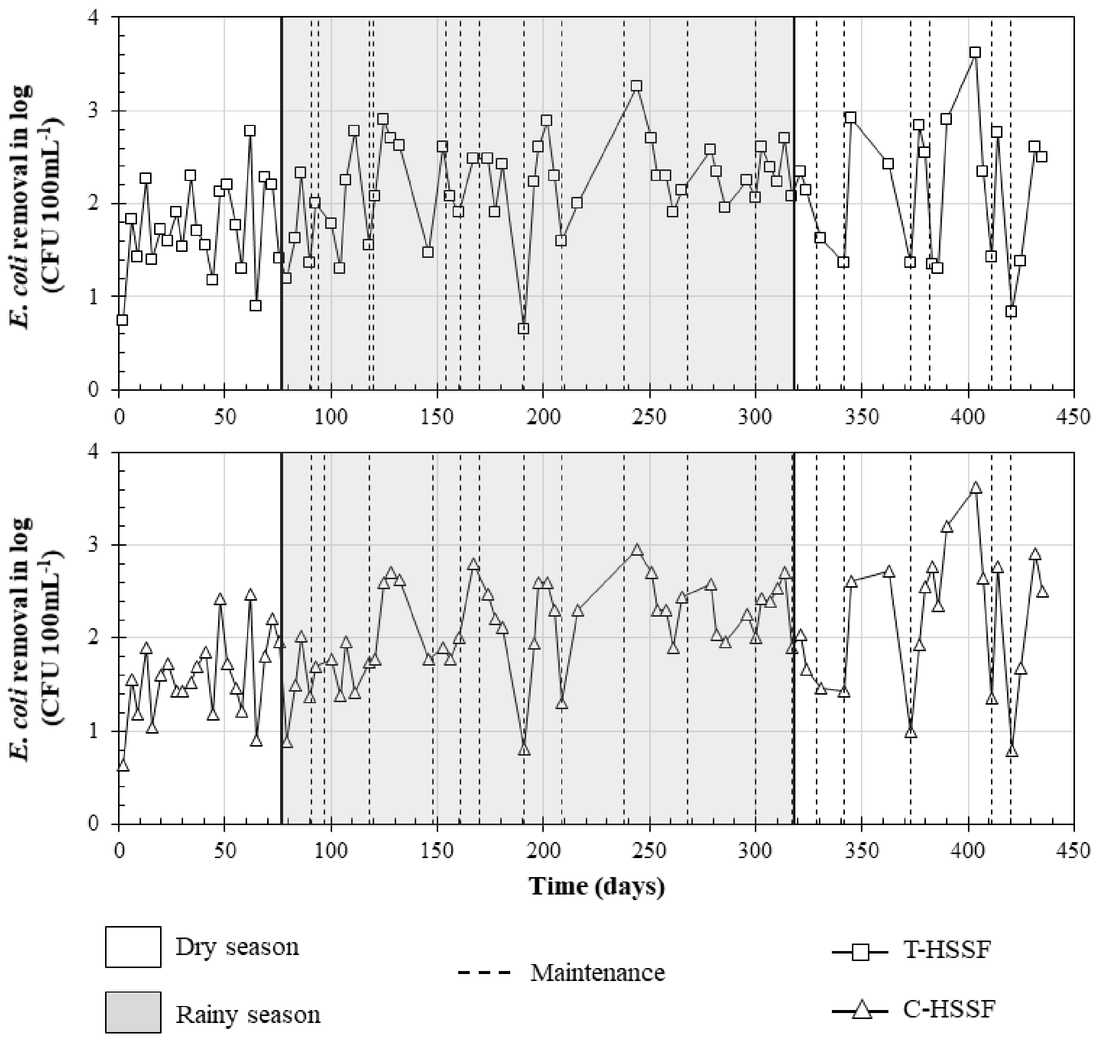

Figure 5. *E. coli* reduction over time in a) traditional model (T-HSSF) and b) compact model (C-HSSF).

T-HSSF and C-HSSF reached a maximum *E. coli* reduction of 3.62 log and means of 2.06 ± 0.60 log and 1.99 ± 0.66 log, respectively, with no statistical difference between the models (p = 0.43). Young-Rojanschi and Madramootoo (2014) observed that increased filter media depths result in improvements of HSSF performance for *E.*

coli reduction. As expected, the most effective zone for *E. coli* reduction was the first 5 cm, corresponding to the *Schmutzdecke*, followed by the 5-30 cm and 30-55 cm. The first zone reduced *E. coli* by 2.2 log, the second by 1.0 log and the third by 0.5 log. Based on this, the T-HSSF should perform significantly higher than C-HSSF due to its longer filter media. In our study, the addition of the non-woven synthetic fabric, positioned at the filters' media top, was able to maintain the reduction performance. The fabric served as a support medium for a more robust *Schmutzdecke* at the top, which enables bacteria retention similar to those obtained by an additional 25 cm of media length.

HSSF ripening was not visually evident in Figure 5, since natural fluctuations in river water quality during the operation time produced different *E. coli* influent values, which influenced the reduction efficiencies. As increased reduction was expected over time (Elliott et al., 2008), HSSF ripening was verified by Spearman's correlation between the operation time and *E. coli* reduction in Table S1 (i.e. time, T-HSSF $p = 0.015$ and C-HSSF $p < 0.001$, in supplementary material).

On the 2nd day of operation, both filter models removed less than 1.0 log. The performances improved over time as an impact of filter ripening and, from the 174th day, the HSSFs started to produce water with < 1.0 CFU (100 mL^{-1}). This pattern was maintained until the end of the operation time, except for the days with *E. coli* peaks in pre-treated water and after maintenance. T-HSSF and C-HSSF produced water with the absence of *E. coli* in 48% and 43% of the samples, respectively.

HSSF efficiency in *E. coli* reduction decreased after maintenance. However, the microorganism accumulation below the top filter media provided conditions for a faster efficiency recovery (Maciel and Sabogal-Paz, 2020). As a result, the time after the maintenance was not correlated with *E. coli* reduction in any filter model (Table S2, supplementary material). Napotnik et al. (2017) also found no correlation between *E. coli* reduction and time after maintenance in another long-term study (9 months).

Even though HSSF removal values suggest a lower efficiency in the dry season when compared to the rainy season (T-HSSF: 2.15 ± 0.52 log vs 2.60 ± 0.63 log and C-HSSF: 2.12 ± 0.58 log vs 2.55 ± 0.56 log), there were no statistical differences between seasons in both filter models (T-HSSF: $p = 0.07$ and C-HSSF: $p = 0.15$).

T-HSSF and C-HSSF reached average values for total coliform removal of 2.38 ± 0.62 log and 2.34 ± 0.61 log, respectively ($p = 0.65$). The sand media depth in HSSFs did not impact total coliform removal as shown by Bellamy et al. (1985) and Buzunis (1995) in slow sand filters. These findings are in agreement with Mwabi et al. (2012), who maintained a total coliform reduction ranging from 2.0 to 4.0 logs in HSSFs, even with a reduced filter media (15 cm). Although log values achieved by both models regarding total coliforms were similar to *E. coli*, the filtered water samples showed values of total coliforms almost 10 times greater than *E. coli* (Table 3). Bacteria in filtered water samples highlight the need for disinfection.

3.4.4 Protozoa removal

Results of analytical quality assays (Table S2, supplementary material) for *Giardia* cysts and *Cryptosporidium* oocysts were in accordance with the Method 1623.1 (USEPA, 2012). Standard deviations and average protozoa removals for both filter models are shown in Figure 6. It can be observed that the samples were collected in different stages of biological development within the filters, which resulted in the standard deviations for protozoa reductions.

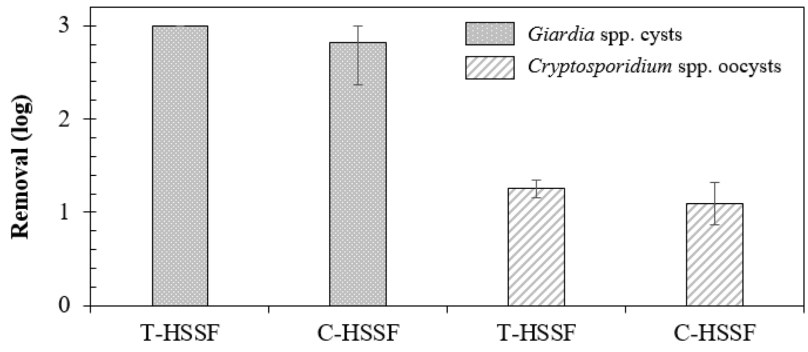

Figure 6. Average values of *Giardia* spp. cyst and *Cryptosporidium* spp. oocyst removals in the traditional model (T-HSSF) and compact model (C-HSSF). Error bars show standard deviations.

As expected, HSSFs achieved higher removals of *Giardia* spp. cysts than *Cryptosporidium* spp. oocysts (Table 3 and Figure 6) due to the larger size (Adeyemo et al., 2015; Medeiros et al., 2020; Palmateer et al., 1999; USEPA, 2012). T-HSSF removed more than 3 log of *Giardia* cysts and 1.25 ± 0.10 log of *Cryptosporidium* spp. oocysts, while C-HSSF removed 2.82 ± 0.45 log of cysts and 1.09 ± 0.23 of oocysts. Although the models were not statistically different (Table 3), T-HSSF achieved complete removal of *Giardia* cysts during 106 days of inoculation.

Other studies also observed complete removal of *Giardia* cysts in HSSF with a sand depth similar to T-HSSF (Palmateer et al., 1999), and their presence in an HSSF with a reduced filter media of 25 cm (Medeiros et al., 2020). Results indicated that the sand depth might be important for retaining the cysts.

On the other hand, thicker media did not show a significant improvement in oocyst removals and no HSSF model accomplished complete removal. The performances obtained by Adeyemo et al. (2015), Medeiros et al. (2020), and Palmateer et al. (1999) were in accordance with our study since both also found oocysts in the filtered water from HSSF with 15 to 50 cm bed thickness, respectively.

3.5 Disinfection performance

Filtered water samples from both filters were disinfected due to their microbiological risk caused by bacteria (total coliforms and *E. coli*) and protozoa (*Giardia* cysts and *Cryptosporidium* oocysts). Table S3 (supplementary material) shows the means and standard deviations of treated water quality.

Despite the absence of *E. coli* in all samples, there were still total coliforms in treated water. Protozoa inactivation of T-HSSF was not applicable due to its absence in filtered water samples. On the other hand, results demonstrated that chlorine was not effective in inactivating protozoa from C-HSSF. In our case, a higher dosage of chlorine could equal the contact time deficit, improve the disinfection performance and reduce the microbiological load (Adeyemo et al., 2019); however, this could make water unfit for human consumption. Both treated water samples had 1.2 ± 0.4 mg L^{-1} of free residual chlorine, a value significantly higher than 0.5 mg L^{-1}, which is recommended by the WHO (1985).

3.6 *Schmutzdecke* evaluation

SEM photomicrographs before and after the filter operation are shown in Figure 7. The images display a particle accumulation on the blanket fibres of T-HSSF (Figure 7 c, and d) and C-HSSF (Figure 7 e, and f), compared to the clean blanket (Figure 7 a, and b). The blankets served as a support medium for the adherence of particles, microorganisms, and extracellular polymeric substances, which supported the biological layer development and a more robust *Schmutzdecke* at the filter media top. No difference was observed in SEM images between T-HSSF and C-HSSF.

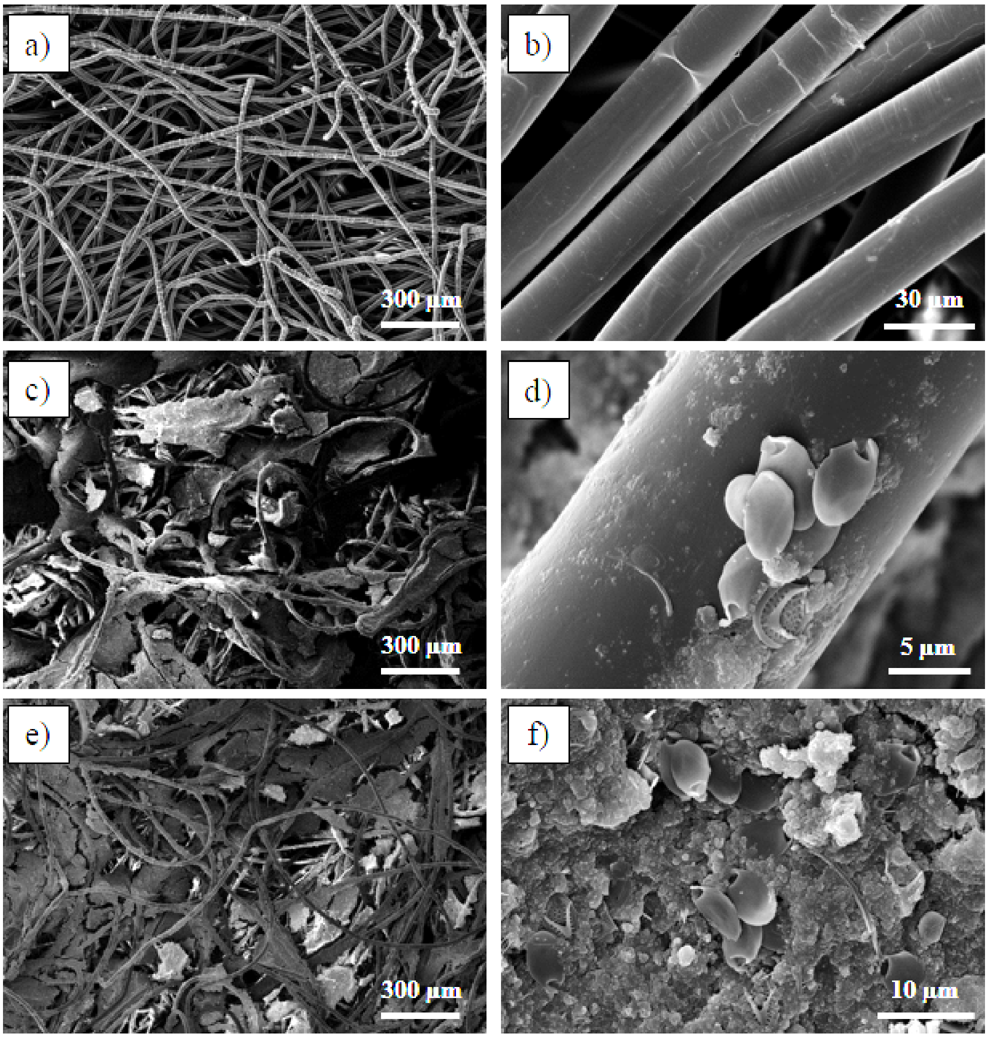

Figure 7. SEM photomicrographs of fabrics. Clean blanket before operation (a and b), after T-HSSF operation (c and d) and after C-HSSF operation (e and f).

Volatile suspended solids (VSS) measurements quantified the particle accumulation in the blankets, displayed by SEM images, and in the sand's first millimetres. The VSS values of the T-HSSF and C-HSSF blankets were 0.45 ± 0.15 g/L and 0.49 ± 0.15 g/L, respectively, while the VSS of T-HSSF and C-HSSF sands were 0.33 ± 0.08 g/L and 0.33 ± 0.11 g/L. Although there was no significant difference ($p > 0.05$) between the filter models and sample type, the VSS from the blankets were higher than sand for both models, demonstrating the importance of the fabric for performance improvement.

Schmutzdecke microscopy analyses showed similar microorganisms from the fabric and sand's first millimetres for both T-HSSF and C-HSSF. Algae was the most significant group, both in variety of genera/species and number, in all samples; however, protozoa, rotifers, helminths, and micro crustaceans were also observed (Table S4, supplementary material). The presence of certain groups of microorganisms in the biofilm is directly related to the microbiological characteristics of the incoming water (Snelling et al., 2006). Algae play a fundamental role in *Schmutzdecke* development, since they are primary colonizers and the main basis for the food chain in this microenvironment (Nakamoto et al., 2014). Some protozoa, such as *Vorticel*a spp., and rotifers are also abundant in slow sand filtration (Lloyd, 1974) and have fundamental importance in biofilm ecology, as they prey on smaller microorganisms (*e.g., Giardia* cysts and *Cryptosporidium* oocysts (Bichai et al., 2014; Siqueira-Castro et al., 2016). The presence of phytoplankton and zooplankton communities highlighted the biological layer development in both fabric and sand.

4 Conclusions

- The pre-treatment by sedimentation and passage through blankets was effective to reduce turbidity from river water.
- Proposed household water treatment achieved removal efficiencies of more than 87% of turbidity, 2.97 log of *E. coli*, 3.32 log of total coliforms, 2.82 log of *Giardia* cysts and 1.13 log of *Cryptosporidium* oocysts.

- The filters' performances pointed out that continuous HSSF might reduce filter media depth without affecting the quantity and quality of filtered water. The only impact caused by the reduced depth was the passage of *Giardia* cysts through the thinner media on one evaluation day.
- Despite providing better bacterial quality of treated water and less risk of recontamination (free residual chlorine), chlorine disinfection may not be the most viable, due to its low efficiency in inactivating protozoa.
- Further research is recommended to improve *Giardia* cyst removal in the compact model, and other safer techniques should be assessed as HSSF post-treatment.

5 Acknowledgements

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6 Statement

The authors hereby declare previous originality check, no conflict of interest and open access to the repository of data used in this paper for scientific purposes.

7 Supplementary Material

Disinfection tests, *Schmutzdecke* microscopy analyses, statistical analysis and analytical quality assays used in the study are provided as supplementary material.

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Supplementary material

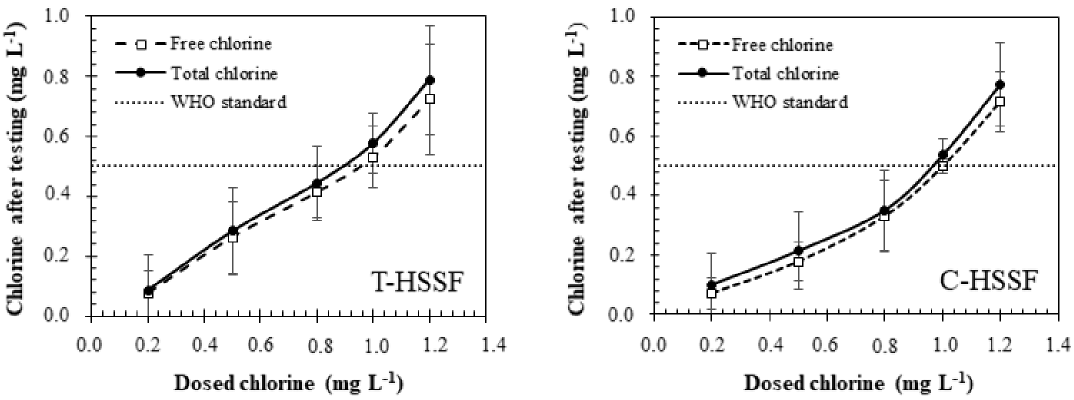

Figure S1 – Disinfection tests using filtered water from T-HSSF and C-HSSF to determine the chlorine dosage in order to reach 0.5 mg L^{-1} of free residual chlorine.

Table S1 – Spearman's correlation coefficients (r) between turbidity, total coliforms and *E. coli* of filtered water samples with HSSFs operating parameters.

Parameter	Model type		Turbidity		Total coliforms		*E. coli*	
			Value	R (%)	Value	R (log)	Value	R (log)
Time (days)	T-HSSF	p	**< 0.001**	**< 0.001**	0.052	**0.002**	0.077	**0.015**
		|r|	**0.346**	**0.514**	0.204	**0.328**	0.189	**0.258**
	C-HSSF	p	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.041**	**< 0.001**
		|r|	**0.349**	**0.541**	**0.427**	**0.472**	**0.217**	**0.431**
A. M. time (days)	T-HSSF	p	**0.001**	0.632	**0.026**	0.921	**0.018**	0.912
		|r|	**0.212**	0.030	**0.233**	0.010	**0.250**	0.012
	C-HSSF	p	**< 0.001**	0.275	0.315	0.604	0.188	0.865
		|r|	**0.228**	0.069	0.106	0.055	0.141	0.018
Influent turbidity (NTU)	T-HSSF	p	**< 0.001**	**0.008**	0.455	0.097	0.304	0.087
		|r|	**0.494**	**0.165**	0.080	0.177	0.111	0.184
	C-HSSF	p	**< 0.001**	0.197	0.243	0.053	0.889	0.267
		|r|	**0.534**	0.081	0.125	0.206	0.015	0.120
Influent total coliforms (CFU 100mL^{-1})	T-HSSF	p	0.913	0.119	0.235	**< 0.001**	0.815	**0.026**
		|r|	0.012	0.168	0.126	**0.477**	0.025	**0.236**
	C-HSSF	p	0.609	0.273	0.063	**< 0.001**	0.990	0.087
		|r|	0.055	0.126	0.063	**0.508**	0.001	0.182
Influent *E. coli* (CFU 100mL^{-1})	T-HSSF	p	0.734	0.058	0.556	0.120	0.354	**< 0.001**
		|r|	0.036	0.204	0.062	0.164	0.099	**0.532**
	C-HSSF	p	0.853	0.058	0.699	**0.018**	0.383	**< 0.001**
		|r|	0.020	0.200	0.041	**0.247**	0.094	**0.481**

Notes: time: 436 days of operation; A. M. Time: days after maintenance; T-HSSF: traditional model; C-HSSF: compact model; p-value: probability of non-correlation; |r|: Spearman's correlation coefficient modulus; and R: removal. Significant correlation in bold.

Table S2 – Results of analytical quality assays compared with USEPA criteria.

	Giardia spp. cysts		*Cryptosporidium* spp. oocysts	
	Recovery (%)	Variation coefficient (%)	Recovery (%)	Variation coefficient (%)
Analytical assay	8.1	52.5	33.8	29.9
USEPA (2012)	8 - 100	≤ 97	32 - 100	≤ 46

Notes: blank tests presented no cysts and oocysts

Table S3 – Filtered water samples from T-HSSF and C-HSSF disinfected by hypochlorite sodium.

Parameter	Filtered water	Treated water	Inactivation (I) or Variation (V)	p-value	
	Mean ± Standard Deviation				
***Escherichia coli* CFU 100 mL^{-1})**					
T-HSSF	6 ± 12	Absence	0.36 ± 0.74 log (I)	**< 0.05**	0.36
C-HSSF	6 ± 10	Absence	0.52 ± 0.64 log (I)	**< 0.05**	
Total coliforms (CFU 100 mL^{-1})					
T-HSSF	28 ± 38	6 ± 6	0.63 ± 0.44 log (I)	**< 0.05**	0.33
C-HSSF	27 ± 29	7 ± 6	0.51 ± 0.45 log (I)	**< 0.05**	
***Giardia* cysts (cysts 24 L^{-1})**					
T-HSSF	Absence	Absence	N/A	N/A	
C-HSSF	1 ± 2	1 ± 3	0.06 ± 0.14 log (I)		
***Cryptosporidium* oocysts (oocysts 24 L^{-1})**					
T-HSSF	5 ± 4	10 ± 4	N/A	N/A	
C-HSSF	12 ± 9	12 ± 7	0.04 ± 0.10 log (I)		
Turbidity (NTU)					
T-HSSF	2.76 ± 5.08	2.75 ± 5.49	1 ± 17 % (V)	0.92	0.71
C-HSSF	3.12 ± 6.10	3.01 ± 5.50	1 ± 19 % (V)	0.97	
Apparent colour (HU)					
T-HSSF	12.6 ± 22.3	11.3 ± 23.5	33 ± 34 % (V)	0.36	0.74
C-HSSF	16.8 ± 35.8	12.5 ± 25.2	30 ± 29 % (V)	0.36	
True colour (HU)					
T-HSSF	9.0 ± 16.2	7.7 ± 16.1	38 ± 30 % (V)	0.49	0.70
C-HSSF	11.0 ± 23.9	8.2 ± 16.1	32 ± 40 % (V)	0.66	
Absorbance (λ = 254 nm)					
T-HSSF	0.039 ± 0.042	0.033 ± 0.041	17 ± 11 % (V)	0.26	0.12
C-HSSF	0.043 ± 0.058	0.036 ± 0.041	11 ± 12 % (V)	0.58	
Temperature (°C)					
T-HSSF	21 ± 2	19 ± 2	7 ± 6 % (V)	**< 0.05**	0.43
C-HSSF	20 ± 2	19 ± 2	6 ± 6 % (V)	**0.05**	
pH					
T-HSSF	7.11 ± 0.14	6.96 ± 0.16	2 ± 1 % (V)	**< 0.05**	0.36
C-HSSF	7.14 ± 0.13	6.95 ± 0.15	3 ± 1 % (V)	**< 0.05**	
Total alkalinity					
T-HSSF	17.6 ± 1.4	15.7 ± 1.5	11 ± 6 % (V)	**< 0.05**	0.95
C-HSSF	17.3 ± 1.4	15.5 ± 1.5	10 ± 6 % (V)	**< 0.05**	
Total organic carbon (mg L^{-1})					
T-HSSF	2.12 ± 0.32	2.06 ± 0.26	2 ± 11 % (V)	0.53	**0.04**
C-HSSF	2.05 ± 0.31	2.14 ± 0.23	6 ± 11 % (V)	0.36	
Electrical conductivity (µS cm^{-1})					
T-HSSF	45.62 ± 6.72	66.93 ± 9.25	- 47 ± 9 % (V)	**< 0.05**	0.55
C-HSSF	45.12 ± 6.98	67.14 ± 9.92	10 ± 3 % (V)	**< 0.05**	
Dissolved oxygen (mg L^{-1})					
T-HSSF	8.2 ± 0.3	8.0 ± 0.3	2 ± 3 % (V)	**0.15**	0.51

C-HSSF	8.3 ± 0.3	8.1 ± 0.3	3 ± 3 % (V)	**0.05**	
Zeta potential (-mV)					
T-HSSF	18.9 ± 2.8	21.7 ± 7.5	- 14 ± 31 % (V)	0.51	0.84
C-HSSF	20.3 ± 8.0	22.3 ± 2.2	20 ± 37 % (V)	0.64	
Particle size (nm)					
T-HSSF	236.9 ± 8.4	244.1 ± 6.7	- 3 ± 4 % (V)	0.23	**0.04**
C-HSSF	286.5 ± 33.3	278.1 ± 31.1	3 ± 2 % (V)	0.73	

Note: N/A not applicable

Table S4 – Microorganisms identified by bright field microscopy in samples collected from fabric and sand from T-HSSF and C-HSSF

Biological class	Microorganisms	T-HSSF		C-HSSF	
		Fabric	**Sand**	**Fabric**	**Sand**
Algae	*Ankistrodesmus* spp.		X		
	Apatococcus spp.			X	
	Aulacoseira spp.	X	X	X	X
	Chlorella spp.	X	X	X	X
	Chrysamoeba spp.			X	
	Closterium spp.	X		X	X
	Coelastrum spp.			X	
	Cosmarium spp.			X	
	Desmodesmus spp.		X	X	X
	Diatoma spp.	X	X	X	X
	Eremosphaera spp.				X
	Euglena spp.	X	X	X	X
	Gomphonema spp.				X
	Melosira spp.	X			
	Monoraphidium spp.	X	X		
	Navícula spp.	X	X	X	X
	Nitzchia spp.		X	X	X
	Pediastrum spp.	X	X		X
	Phacus spp.	X	X	X	X
	Pleurosigma spp.		X	X	X
	Scenedesmus spp.	X	X	X	X
	Staurastrum spp.	X	X		X
	Synedra spp.	X	X	X	X
	Tabellaria spp.	X		X	
	Tetrastrum spp.			X	
	Trachelomonas spp.		X	X	X
	Ulothrix spp.			X	
Helminths	Nematode (larvae)	X		X	X
	Nematode (egg)			X	
Protozoa	Ciliated protozoa			X	
	Coleps spp.			X	X
	Corythion spp.	X	X	X	X
	Crytosporidium spp. oocysts				X
	Cyclotella spp.		X	X	X
	Heliozoa	X	X	X	X
Others	Microcrustacean	X	X	X	X
	Rotifer	X	X	X	
	Vorticella spp.	X	X	X	X