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Title: Household slow sand filters in intermittent and continuous flow for a long-term surface water treatment: efficiencies assessment and operational challenges

Short title: HSSF for a long-term surface water treatment

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Abstract

The Household Slow Sand Filter (HSSF) is a Point-Of-Use technology that has several technical, constructive, and operational advantages, which allows users to improve the quality of their own drinking water at home. This paper aims to provide results concerning the real possibility of treating surface water using HSSF with two feeding strategies, covering more than one year of operation (430 days), including seasons with different inputs on surface water. To do this, we compared the intermittent (HSSF-I) and the continuous (HSSF-C) feeding strategies in quantitative terms (filtered water quality and treatment efficiency) and qualitative terms (construction, cost, and operational challenges). Overall, both HSSF models were efficient and improved the water quality, but HSSF-C produced better quality filtered water in terms of turbidity (73 (± 20)% versus 69 (± 18)%), *Escherichia coli* (2.06 (± 0.60) log versus 1.65 (±

0.78) log), *Giardia* cysts (>3 log versus 2.89 (± 0.32) log), and *Cryptosporidium* oocysts (1.22 (± 0.10) log versus 0.95 (± 0.45) log) than HSSF-I. In addition, HSSF-C was able to remain more stable throughout the entire operation, without major impacts caused by influent water variations and maintenance activities. On the other hand, HSSF-I was cheaper, took up less space in the house, had a simple and easy operation, and did not require as much maintenance as the continuous one. Results indicated that HSSF-C may be a more viable model for treating surface water, but it still needs to improve its transfer requirements and assess its user acceptability from field experiences.

Keywords: biosand filter, drinking water, Point-Of-Use, safe water, slow sand filtration, Sustainable Development Goal 6

1. Introduction

The 2030 Agenda for the Sustainable Development Goals (SDG) aim at ending poverty in all forms including through access to clean water and sanitation (SDG 6). Despite advances in recent years to achieve SDG 6, the World Health Organization (WHO) still reports that 10% of the world's population (i.e., 765 million people) do not have access to clean water services (WHO and UNICEF, 2019), which is a worldwide concern that highlights health, social and economic disparities, especially in low- and middle-income countries.

Currently, there are several effective techniques for water treatment, but each of them is more feasible for a given scenario and location. Communities in a state of vulnerability, whether caused by geographic isolation or an economic situation, require water treatment technologies that are adaptable to their social and economic context. In these cases, Point-Of-Use (POU) technologies can be attractive solutions, as their premise is to enable users without technical training to treat their own drinking water at home through simple, safe and low-cost methods.

A promising example of POU is the Household Slow Sand Filter (HSSF), a 30-year old technology, which has many field lessons and improvements, including several technical, constructive, and operational advantages (Freitas et al., 2022). Due to the HSSF purification mechanisms through physical, chemical, and biological processes that are quite similar to the conventional slow sand filter, HSSF is also able to retain particles and remove organic/inorganic compounds and several disease-causing pathogens at acceptable levels for drinking water supply (CAWST, 2012; Freitas et al., 2022).

Currently, there are different HSSF designs, comprising different materials and of different sizes. Among these different designs, studies have reported two different flow regimes: intermittent and continuous flows (Freitas et al., 2022). The intermittent flow regime (HSSF-I) is characterized by the simplified feeding of the filters, which is carried out in batches according to the user's needs. On the other hand, the continuous flow regime (HSSF-C) is characterized by a constant pumping or gravity feed (i.e., from an elevated reservoir).

Because of these feeding strategies, the HSSF-I is easier to operate (it only needs manual efforts by users), simple, low-cost, while the HSSF-C requires electricity or a larger space inside the residence for the reservoir, as well as more personal training and a higher cost (Sabogal-Paz et al., 2020; Freitas et al., 2002). Despite the drawbacks, the constant and lower filtration rate of the HSSF-C model promotes more stable conditions for the *schmutzdecke* development, in addition to greater efficiencies in the removal of turbidity, bacteria, and protozoa (Andreoli and Sabogal-Paz, 2020; Young-Rojanschi and Madramootoo, 2014). As they are more efficient, continuous filters are less dependent on the influent water quality than intermittent ones (Maciel and Sabogal-Paz, 2020), however, their developed biological layer is more sensitive to interruptions in the supply (i.e., events with the unavailability of water) than intermittent filters (Freitas and Sabogal-Paz, 2020).

Furthermore, the HSSF-I was designed in the early 1990s (Lee, 1991), and therefore, for approximately 30 years it has been investigated and improved by several laboratory studies and field tests, while the HSSF-C is still a recent model that has less than 10 years of observations (Young-Rojanschi and Madramootoo, 2014), no deployments reported in target communities, and several gaps that require further studies. Therefore, there are no complete studies on the ability of HSSF-C to treat some contaminants/pollutants, nor its long-term sustainability and limitations. Considering its better efficiency, the HSSF-C capacity should be better explored, mainly concerning the gaps, to extend scientific knowledge, minimize the disadvantages and evaluate the potential of this regime in the field.

In the peer-reviewed literature, there are currently only nine scientific papers that compare HSSF-I and HSSF-C performances, two studies on bench-scales (Young-Rojanschi and Madramootoo, 2014; Sabogal-Paz et al., 2020) and seven studies on full-scales. In three studies, the HSSF were fed with simulated water (Terin and Sabogal-Paz, 2019; Maciel and Sabogal-Paz, 2020; Freitas and Sabogal-Paz, 2020), one with groundwater (Andreoli and Sabogal-Paz, 2020), two with surface water for a short-term, up to 48 days of operation (Fava et al., 2022; Lubarsky et al., 2022), and one with surface water for eight months of operation (Lamon et al., 2021).

All provided important scientific knowledge for improving the HSSF (Table 1), especially Andreoli and Sabogal-Paz (2020) who evaluated the technical capacity for long-term groundwater treatment using surface water weekly as a ripening agent, and Lamon et al (2021) who observed that both HSSF regimes effectively develop and mature the *schmutzdecke* when treating surface water. The latter focused on dissolved oxygen microprofiles measured by microsensors, therefore the efficiency assessment was only a superficial and secondary analysis. Despite advances in the literature in recent years, there is still no consistent, long-term and comprehensive study comparing the two flow regimes for surface water treatment.

Table 1 – Peer-reviewed literature comparing HSSF-I (intermittent flow) and HSSF-C (continuous flow) for water treatment.

Reference	Operating parameters				Main conclusions	
	Scale	MRF ($m^3.m^{-2}.d^{-1}$)	Influent	Days	Efficiency	Remarks
Young-Rojanschi and Madramootoo (2014)	Bench	HSSF-I: 16.6 HSSF-C: 0.24	Surface water	58	Turbidity and *E. coli*: HSSF-C > HSSF-I	First paper reporting HSSF-C; The low and constant filtration rate provided better efficiency results for HSSF-C.
Terin and Sabogal-Paz (2019)	Full	HSSF-I: 2.95 HSSF-C: 1.22	Simulated reservoir water	63	Cyanobacteria and cyanotoxin: HSSF-I ~ HSSF-C	Both removed *M. auerinosa* and cyanotoxin microcystin-LR from water.
Sabogal-Paz et al. (2020)	Bench	HSSF-I: 21.0 HSSF-C: 0.38	Simulated rainwater	90	Bisphenol A: HSSF-I > HSSF-C	HSSF-I showed low efficiency in BPA removal and HSSF-C did not remove it; Techniques to accelerate ripening are encouraged for the treatment of water with low organic and

						inorganic loads.
Maciel and Sabogal-Paz (2020)	Full	HSSF-I: 4.6 (with) and 9 (without float) HSSF-C: 0.68	Simulated clean water	170	Turbidity: HSSF-I > HSSF-C *E. coli*: HSSF-C > HSSF-I	The float reduced the maximum filtration rate, accelerating the biolayer maturation; The blanket at the sand top extended the filtration run and made maintenance activities easier.
Freitas and Sabogal-Paz (2020)	Full	HSSF-I: 2.79 HSSF-C: 1.22	Simulated surface water	75	Turbidity: HSSF-C > HSSF-I *E. coli*: HSSF-I > HSSF-C	Surface water quality required a pre-treatment; Both HSSFs are sensitive to long periods (> 96h) without feedings, with the greatest impacts on turbidity HSSF-I and *E. coli* HSSF-C.
Andreoli and Sabogal-Paz (2020)	Full	HSSF-I: 8.64 HSSF-C: 0.91	Groundwater (plus *E. coli* and protozoa)	374	Turbidity and *E. coli*: HSSF-C > HSSF-I Protozoa: HSSF-I ~ HSSF-C	River water weekly as a ripening agent reduced the ripening time by 81 days; Encysted forms of protozoa passed through the filter bed even with ripe *schumuzedecke*.
Lamon et al. (2021)	Full	HSSF-I: 8.81 HSSF-C: 0.90	Pre-treated surface water	240	Turbidity: HSSF-I ~ HSSF-C *E. coli*: HSSF-C > HSSF-I	Paper focused on dissolved oxygen (DO) microprofiles in the *schmutzdecke*; DO microprofiles illustrated a biofilm growth associated with a progressive

						increase in HSSF efficiencies.
Fava et al. (2022)	Full	HSSF-I: 9.0 HSSF-C: 0.90	Pre-treated surface water	30	*E. coli*: HSSF-C > HSSF-I	Both HSSF are able to remove algae, protozoa, and helminths, as well as bacteria, from surface water.
Lubarsky et al. (2022)	Full	HSSF-I: 9.0 HSSF-C: 0.90	Pre-treated surface water	48	Turbidity and *E. coli*: HSSF-I ~ HSSF-C	Both models showed a gradual and ripening mature *schmutzdecke* over 48 days (measured by extracellular polymeric substances, biomass, dissolved oxygen, and microbial community).

Note: MRF – maximum filtration rate

In our paper, we provided a full-scale laboratory comparison between HSSF-I and HSSF-C for a long-term surface water treatment (430 days): the most critical and real situation for an HSSF before implementing it into target communities. The paper aims to address and clarify several crucial points for decision making, based on quantitative (filtered water quality and removal efficiency) and qualitative (operational aspects, maintenance activities, and costs) comparisons. This investigation aims to improve the HSSF-C transfer requirements in target communities, promoting health gains for users, based on an efficient and accessible engineering perspective. To the best of the author's knowledge, this is the first paper to provide results on the real possibility of treating surface water using both HSSF-I and HSSF-C technologies, covering more than one year of operation, including seasons with different inputs of particles and microorganisms on surface water.

2. Materials and methods

2.1. HSSF designs

Four HSSFs were built with polyvinyl chloride (PVC) Defofo pipe (cross-section area = 0.053 m², Ø 250 mm) and PVC fittings (Ø 25 mm), using the Andreoli and Sabogal-Paz (2020) prototype as a base model. The filters had a support layer of 7.5 cm of coarse gravel (7.0 – 12.0 mm), 5 cm of fine gravel (5.0 – 7.0 mm), and 5 cm of coarse sand (0.17 – 0.67 mm), and a filtration layer of 50 cm of fine sand (0.17 – 0.56 mm; effective size 0.17 mm; uniformity coefficient 2.27; porosity 37%). All materials were purchased at hardware stores and gardening centers and previously washed, sun-dried and sieved. Furthermore, we placed a non-woven synthetic fabric (felt blanket) (specific gravity 0.2 g cm^{-3}; 100% polyester; thickness 2 mm) at the top of the filtration layer to improve the filter efficiency and help with maintenance, and a float valve to control the maximum water level and the maximum filtration rate within the filters (Freitas et al., 2022). The difference between filters concerns the operating regime. Two filters were operated in an intermittent flow (HSSF-I) and two in a continuous flow (HSSF-C). The filters were a duplicate of each operating regime. A drawing of HSSF in both flows is shown in Figure 1.

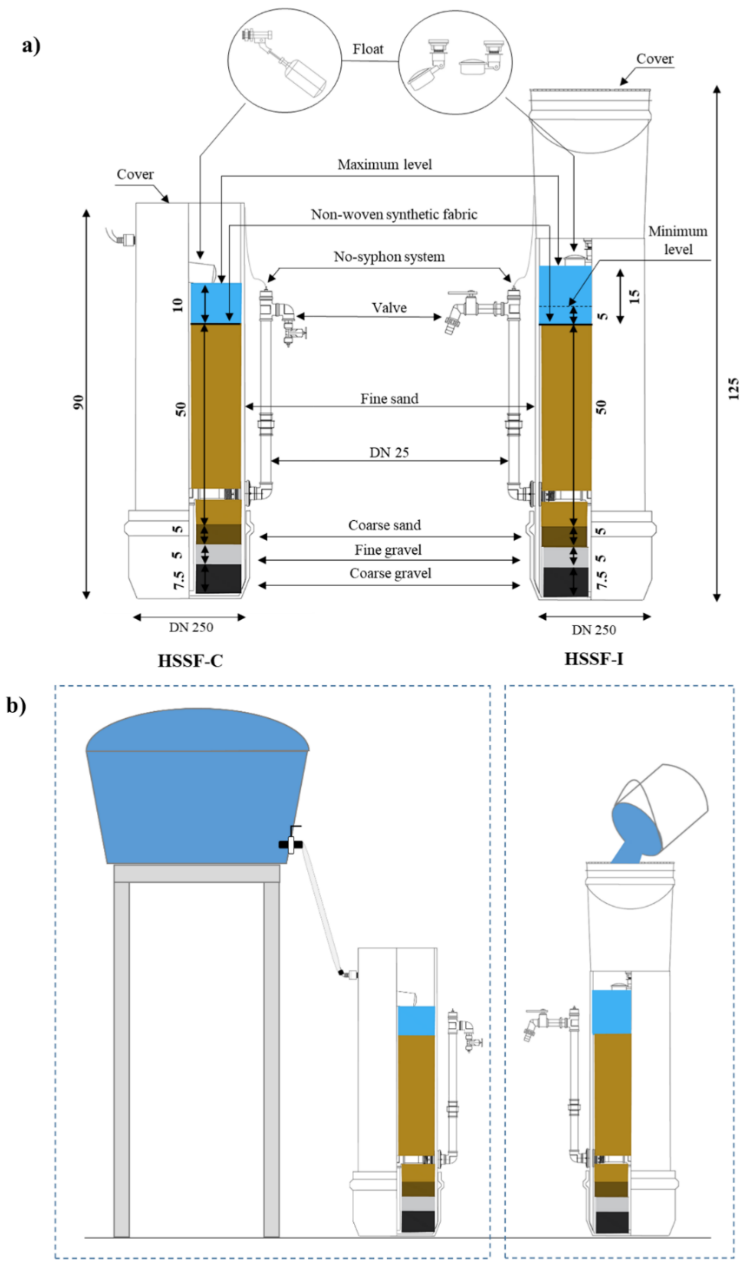

Figure 1 – HSSF in both flows (HSSF-C: continuous flow and HSSF-I: intermittent flow), a) cross-sections, units in centimeters, b) feeding systems (adapted from Lubarsky et al., 2022)

Some differences between the HSSF regimes were the fed system/strategy, water level, and filtration rate patterns (Figure 1). The HSSF-I was fed manually three times a day (8:00 a.m., 1:00 p.m., and 6:00 p.m.) with 16 L each, while the HSSF-C was constantly gravity-fed by a reservoir positioned 1 meter high. The water level ranged from 5 to 15 cm in the HSSF-I and remained constant at 10 cm in the HSSF-C. The filtration rate declined up to zero in the HSSF-I, while that of HSSF-C was kept constant by a needle valve faucet at the filter outlet. Despite the differences, for comparative purposes, both HSSF models produced 48 L d^{-1}, which was considered a minimum daily amount for consumption and food preparation for a family (5.3 L $person^{-1}$ d^{-1}) (Howard et al., 2020).

Prior to the start-up, we performed tracer tests and filtration rate tests on the HSSFs to characterize flow patterns, maximum filtration rate (MFR), time to reach MFR, and total filtration time. These results were previously provided by Freitas et al. (2021) and Terin et al. (2022). Both filter models presented flow patterns considerably closer to the ideal plug-flow and maximum filtration rates lower than the HSSF guidelines (Freitas et al., 2021; Terin et al., 2022; CAWST, 2010). Mean clean sand MRF were 9.0 m^3 m^{-2} d^{-1} for HSSF-I and 0.90 m^3 m^{-2} d^{-1} for HSSF-C. Despite this difference, the filtration rate of HSSF-I dropped to zero at each feeding, while that of HSSF-C always remained the same.

2.2. HSSF operation

Over 430 days, HSSFs were fed with surface water from the Monjolinho River (São Carlos/Brazil) pre-treated by 24-hour sedimentation and filtration through a two-layered non-woven synthetic blanket. 100 L of this pre-treated surface water were pumped into the HSSF-C feed reservoir, and the other 100 L were used to manually feed the HSSF-I. The filtered water produced daily by each HSSF was stored in 50 L tanks, where we collected samples for quality analysis.

As the Monjolinho River had a low protozoa load, after 330 days of operation, we chose to overload the HSSFs with *Giardia* cysts and *Cryptosporidium* oocysts from commercial and purified suspensions (Waterborne® Inc, USA). To do this, we simulated concentrations of contaminated Brazilian springs (Sato et al., 2013) adding 10^3 cysts and 10^2 oocysts directly inside the filters in stationary water.

Over the operating time, particles and microorganisms were retained on the blanket and sand surface, reducing the voids and the daily production. When an HSSF was not able to maintain the 48 L d^{-1}, we performed the unit maintenance by cleaning the blanket and stirring 5 cm from the sand top (Freitas et al., 2022). The maintenance was carried out as follows: 1) closing the outlet valve, 2) removing the dirty synthetic fabric, 3) manually stirring 5 cm from the sand top and consequent removal of the dirty supernatant, 4) scraping and washing the synthetic fabric, 5) placing the fabric inside the unit, 6) adjusting the flow rate (only for HSSF-C), 7) restarting the operation.

In our study, we considered that filters reached their maximum peak particle removal when they required a maintenance activity (i.e., production < 48 L.d^{-1}). Therefore, the ripening time was given as the simple count of how many days filters were able to maintain their full operation without affecting daily production. This ripening time was reset at each maintenance activity.

2.3. Sampling and analysis

We collected influent and filtered waters in 500 mL bottles and analyzed them by physical-chemical and microbiological parameters according to a predetermined frequency (Table 2). Due to the cost per sample and the operational difficulty involved, we assessed the filtered waters for *Giardia* cysts and *Cryptosporidium* oocysts at only six points.

Table 2 – Physicochemical and microbiological analyses performed in water samples

Parameter	**Frequency**	**Methodology/Equipment**
Turbidity	Daily	Turbidimeter 2100N (Hach, USA)
Total coliform	Twice a week	9222 - Membrane filtration (APHA, 2012)
Escherichia coli	Twice a week	
Giardia cysts	Punctual	Method 1623.1 with membrane filtration concentration (USEPA, 2012; Franco et al., 2016)
Cryptosporidium oocysts	Punctual	
Dissolved Organic Carbon	Weekly	TOC-L (Shimadzu, Japan)
Dissolved oxygen	Weekly	Oximeter DO-5519 (Lutron Eletronics, Taiwan)
pH	Weekly	pHmeter DM20 (Digimed, Brazil)
Electrical conductivity	Weekly	Electrical conductivity meter DM32 (Digimed, Brazil)
Absorbance 254 nm	Weekly	DR5000 spectrophotometer (Hach, USA)
Apparent color	Daily	Colorimeter DM-COR (Digimed, Brazil)
True color	Weekly	
Particle size	Monthly	Zetameter ZS90 (Malvern Panalytical, United Kingdom)

We also evaluated the dissolved oxygen (DO) profile along the filter bed. These samples were withdrawn from intakes at six heights (+5 cm above the filter media, -2.5, -32.5, -43.5, and -60.5 cm below the filter media) using syringes without disturbing the liquid. In the profiles, temporal and spatial decays were evaluated, highlighting phases with greater consumption and, consequently, greater microbiological activity.

For comparative purposes, we also quantified ripening times (i.e., time when filter production < 48 L d^{-1}) and cleaning frequencies for each HSSF model. At this point, we discuss the expected efficiency increases until maturation and consequent decay after maintenance activities, as well as the effect of HSSF operation on particle and microorganism retention.

2.4. Statistical analysis

To provide a more representative scenario of each operating strategy, data from each HSSF model were presented and analyzed based on the average values between the duplicates. To determine whether there were significant differences (95%

confidence level, $p < 0.05$) between two datasets, we first evaluated their normality distributions (Shapiro-Wilk test) and then applied hypothesis tests. The normal dataset distributions were compared by the T-test and the non-normal by the Mann-Whitney test.

We also performed bivariate analyses (Spearman correlation) to investigate the correlation between the HSSF performance and operating parameters. For this analysis, the significant correlation was defined when the p-value < 0.05 and the module of Spearman coefficient $|r|$ was greater than the module of r-critical. All statistical analyses were performed on PAST 3.25 software.

2.5. Qualitative data analysis

HSSF-I and HSSF-C were evaluated not only on filtered water quality/treatment performance but also on possible effects on user acceptability (plus sustained use and adherence). To do this, we listed and discussed several strengths and weaknesses of HSSF-I and HSSF-C observed during a long-term surface water treatment, comparing both feeding strategies in terms of construction facilities, cost, and operational challenges. Filter costs were based on Brazilian public spreadsheets, reference budgets, and Internet surveys.

3. Results and discussion

3.1. Quantitative data analysis

The performances of HSSF models, based on their influent and effluent water qualities (mean, minimum, maximum, and median values), are shown in Table 3.

Table 3 – Mean, standard deviation, minimum, maximum and median values of water quality parameters in raw, influent and effluent waters from HSSF-I (intermittent flow) and HSSF-C (continuous flow)

Evaluated parameters	Raw water		Influent water		Effluent water HSSF-I		Effluent water HSSF-C		WHO limits (WHO, 2017)
	Mean (SD)	Min Max Median	Mean (SD)	Min Max Median	Mean (SD)	Min Max Median	Mean (SD)	Min Max Median	
Turbidity (NTU)	26.5 (25.6)	4.91 139 16.6	13.2 (14.6)	3.07 98.1 6.84	3.75 (4.68)	0.54 41.0 2.26	3.13 (4.77)	0.36 42.4 1.76	< 5.0 (Ideally < 1.0)
Total coliforms (CFU/100 mL)	9439 (5611)	1330 27110 8775	5356 (4302)	590 25790 4400	143 (308)	9 2129 59	42 (140)	0 1349 18	Absence
E. coli (CFU/100 mL)	953 (1295)	40 7800 480	332 (511)	20 4200 200	21 (82)	0 725 4	4 (9)	0 54 1	Absence
Giardia cysts (cysts/48 L)	NM		1054 (773)	94 2468 879	1 (2)	0 6 0	0 (0)	0 0 0	Absence
Cryptosporidium oocysts (oocysts/48 L)	NM		248 (128)	87 492 210	41 (41)	6 120 27	15 (3)	10 19 15	Absence
Dissolved Organic Carbon (DOC) (mg/L)	2.47 (0.78)	1.10 4.21 2.61	2.07 (0.87)	0.99 6.05 2.03	1.67 (0.62)	0.40 3.58 1.72	1.85 (0.50)	0.93 3.21 1.93	-
Dissolved oxygen (mg/L)	7.7 (0.5)	6.5 8.7 7.6	7.8 (0.4)	7.0 8.8 7.8	7.8 (0.4)	7.0 8.9 7.8	8.2 (0.4)	7.3 9.0 8.2	-
pH	6.93 (0.14)	6.66 7.32 6.91	7.05 (0.10)	6.85 7.31 7.07	7.13 (0.07)	6.97 7.28 7.12	7.18 (0.09)	6.96 7.41 7.19	6.5 – 8.5
Electrical conductivity (µS/cm²)	49.11 (7.54)	34.66 77.92 47.81	48.61 (6.77)	36.59 67.39 47.97	48.49 (8.64)	35.94 82.31 46.29	48.05 (6.83)	35.56 70.27 47.19	-
Absorbance 254nm	0.111 (0.064	0.051 0.343	0.109 (0.061	0.050 0.322	0.053 (0.039	0.012 0.185	0.054 (0.050	0.013 0.285	-

	)	0.083	)	0.083	)	0.041	)	0.043	
Apparent color (mg Pt Co/L)	79.3 (54.9)	10.3 300 58.3	61.4 (43.2)	13.4 264 43.7	18.0 (18.4)	0 147 13.9	16.1 (23.6)	0 178 10.6	-
True color (mg Pt Co/L)	32.6 (23.7)	6.1 118 21.9	31.4 (21.8)	6.9 103 20.9	12.2 (12.5)	0 60.6 7.9	7.5 (3.6)	2.8 13.5 8.7	15.0
Particle size (nm)	476.1 (269.1)	266.8 1280 425.2	304.8 (90.7)	225.9 543.3 271.8	261.8 (67.0)	170.1 442.1 248.9	285.0 (128.8)	195.4 662.7 242.0	-

Note: NM – not measured

Both models improved river water quality, resulting in effluents with turbidity below 5 NTU and a lower risk of bacteria and protozoa. Nonetheless, using HSSF alone for surface water treatment is still not enough for consumption standards, even in controlled laboratory settings, as none of the models produced safe water according to WHO standards (i.e., microbiological absence and turbidity < 1 NTU; WHO, 2017). Field research shows that when a community builds, operates, and maintains the HSSF, produced filtered water tends to present worsened quality as due to a lack of knowledge, follow-up, and training, not all recommended practices and care are performed (Freitas et al., 2022).

Modifications in HSSF design and operation, as well as the insertion of pre- and post-treatment steps, based on social, cultural, and economic characteristics of target-users, are approaches that can provide improvements to household surface water treatment. As an immediate measure, multi-barrier household systems are strongly advised for surface water treatment given the inability of HSSF alone to produce potable water. A pre-treatment step aims at reducing the particle load in influent, benefiting the effluent turbidity, while post-treatment inactivates effluent pathogens, reducing contamination and cases of diarrheal diseases.

3.1.1. Turbidity

Turbidity graphs obtained in the long-term operation are shown in Figure 2. Average turbidity values were 13.2 (± 14.6) NTU for influent water, 3.75 (± 4.68) NTU for HSSF-I, and 3.13 (± 4.77) NTU for HSSF-C; which reached respective removal values of 69 (± 18)% and 73 (± 20)%. HSSF-I produced turbidity-safe drinking water according to WHO and Brazil standards (i.e., < 1 NTU; WHO, 2017 and BRAZIL, 2021) in 18% of the samples (47 of 265 samples), while the HSSF-C produced it in 27% of the samples (70 of 265 samples). Turbidity less than 5 NTU was achieved in 80% of the HSSF-I samples (212 of 265 samples) and 87% of the HSSF-C samples (227 of 265 samples).

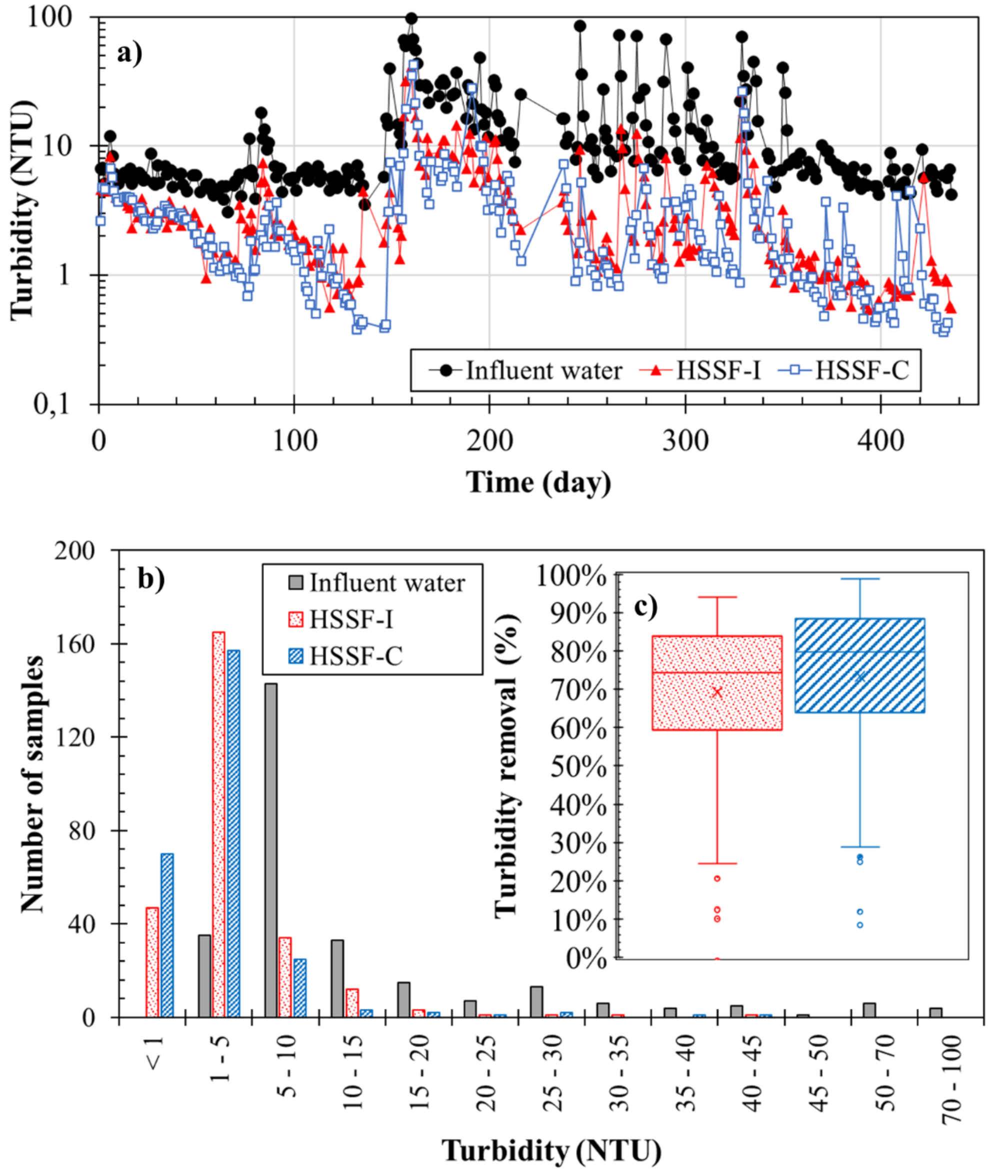

Figure 2 – a) Turbidity values over time for the influent water and filtered waters from HSSF-I (intermittent) and HSSF-C (continuous); b) histogram of the turbidity frequency of the influent water and filtered waters from HSSF-I and HSSF-C, c) box-plot graph showing the removal data by the HSSF-I and HSSF-C.

According to the statistical analysis, there was a significant difference in the turbidity values after the HSSF-I and HSSF-C ($p < 0.01$, Mann-Whitney test). Therefore, in our study, HSSF-C was more efficient to remove turbidity than HSSF-I, and the flow regime significantly influenced the turbidity values even for a long-term surface water treatment. The constant and lower filtration rate (also a lower water speed) of the HSSF-C allowed easier particle retention along the filter bed, and consequently a smaller pass-through. Similar results occurred with HSSF fed by supply waters (Young-Rojanschi and Madramootoo, 2014; Freitas and Sabogal-Paz, 2020; Andreoli and Sabogal-Paz, 2020), greywater (Shaikh and Ahammed, 2021) and secondary treated wastewater (Verma et al., 2017), proving that, regardless of the influent quality, the continuous regime still leads to better conditions for turbidity removal than intermittent ones.

Despite the statistical differences, turbidity reductions over time indicated particle retention in both long-term HSSF operations. Nonetheless, this particle retention also increased head loss (data not shown), making it one of the main contributors to reducing the daily HSSF production. In HSSF-I, the head loss directly affected the MRF values, which showed a very sharp decay from 9.0 $m^3\ m^{-2}\ d^{-1}$ at the beginning of the operation to 2.7 ± 1.7 $m^3\ m^{-2}\ d^{-1}$ at the end. On the other hand, HSSF-C MRF remained at 0.8 ± 0.1 $m^3\ m^{-2}\ d^{-1}$. The head loss in the continuous operation affected the filter's run time, which ranged from 7 to 90 days, requiring 18 maintenance activities during the 430 days. HSSF-I's run time ranged from 12 to 155 days, demanding only ten maintenance sessions during the long-term. In other words, over time, HSSF-I users have to wait longer to produce the same daily volume of filtered water, while HSSF-C users have to carry out more and more frequent maintenance activities. Furthermore, users must expect an increase in the filtered water turbidity after each maintenance activity, which in our study was 18 ± 28% in the HSSF-I effluent and 26 ± 16% in the HSSF-C effluent. These operational counterpoints must be anticipated and supported by training and follow-up in future implementations.

Overall, average ripening times were 42 days for HSSF-I and 23 days for HSSF-C, close to the 30 days reported in the HSSF literature for the *schmutzdecke* development (CAWST, 2012). The HSSF-I longer ripening time was expected, as it had a higher MRF, lower particle retention, and, consequently, a longer time to reach clogs. On the other hand, the HSSF-C filter run was shortened because of the large amounts of particles trapped from the surface water associated with a very low MRF applied.

To better understand the particle retentions, we correlated the filtered water turbidities from HSSF-I and HSSF-C with the influent water turbidity, operating time (i.e., 430 days) and ripening times (Table 4).

Table 4 – Spearman's correlation coefficient (r) between turbidity values from HSSF-I (intermittent) and HSSF-C (continuous) with three operating parameters.

	Influent water	Operating time	Ripening time
HSSF-I	**0.603***	- 0.373*	- 0.434*
HSSF-C	0.494*	- 0.346*	- 0.265*

Notes: * indicates a correlation (p-values < 0.05). Bold indicates a strong correlation. Ripening time is the time when filter production < 48 L d^{-1}.

The results indicated a positive correlation between filtered and influent waters, and a negative correlation between filtered water and operating and ripening times. In addition, different grades of correlation were observed: weak ($0.2 < r < 0.39$), moderate ($0.40 < r < 0.59$) and strong ($0.60 < r < 0.79$).

For HSSF-I samples, correlation module values obtained were: influent water > ripening time > operating time, while for HSSF-C samples were: influent water > operating time > ripening time. Therefore, regardless of the operation, influent water turbidity correlated more with filtered water turbidity than operating and ripening times. In other words, a long-term operation of mature filters was not necessarily decisive for improving the filtered water quality in none of the models, nor did maintenance activities have much effect on filter efficiency, mainly because of variations in influent water quality. This result demonstrates the challenge of treating surface water at home scale and shows the importance of using as clean a source of water as possible as an input matrix in HSSF (CAWST, 2012; Freitas et al., 2021; Terin et al., 2022). Improvements in the household pre-treatment techniques should be further explored, especially those that are simpler, low-cost and easy to operate.

Moreover, turbidity values from HSSF-I obtained higher correlation coefficients for operating and ripening times than those of HSSF-C, i.e., for a long-term surface water treatment, the intermittent was more dependent on the operational parameters than the continuous ones. Until now, the HSSF literature had indicated the opposite (Maciel and Sabogal-Paz, 2020), but the surface water matrix complexity has shown to be a challenge to the most simplified filter: HSSF-I. Therefore, when there is only access to surface water, in addition to pre-treating the water, the users should prioritize continuous filters for a more effective turbidity treatment. However, their operational counterparts (cost, living space, electricity) must be questioned and evaluated in the field with the target community.

3.1.2. Bacteria

E. coli graphs obtained in the long-term operation are shown in Figure 3. Average *E. coli* values were 332 (± 511) CFU 100mL^{-1} for influent water, 21 (± 82) CFU 100mL^{-1} for HSSF-I, and 4 (± 9) CFU 100mL^{-1} for HSSF-C, which reached respective *E. coli* removal values of 1.65 (± 0.78) log and 2.06 (± 0.60) log. The absence of *E. coli*, as recommended by WHO (2017) and Brazil (2021) for safe drinking water, was achieved in 25% of the HSSF-I samples (22 of 89 samples) and in 44% of the HSSF-C samples (44 of 91 samples). HSSF-I took 26 (± 27) days to produce this water free of *E. coli*, while HSSF-C took just 16 (± 13) days. On average, HSSF-I produced moderate risk water (10 to < 100 CFU 100 mL^{-1}) and HSSF-C low risk water (1 to < 10 CFU 100 mL^{-1}) (WHO, 2004).

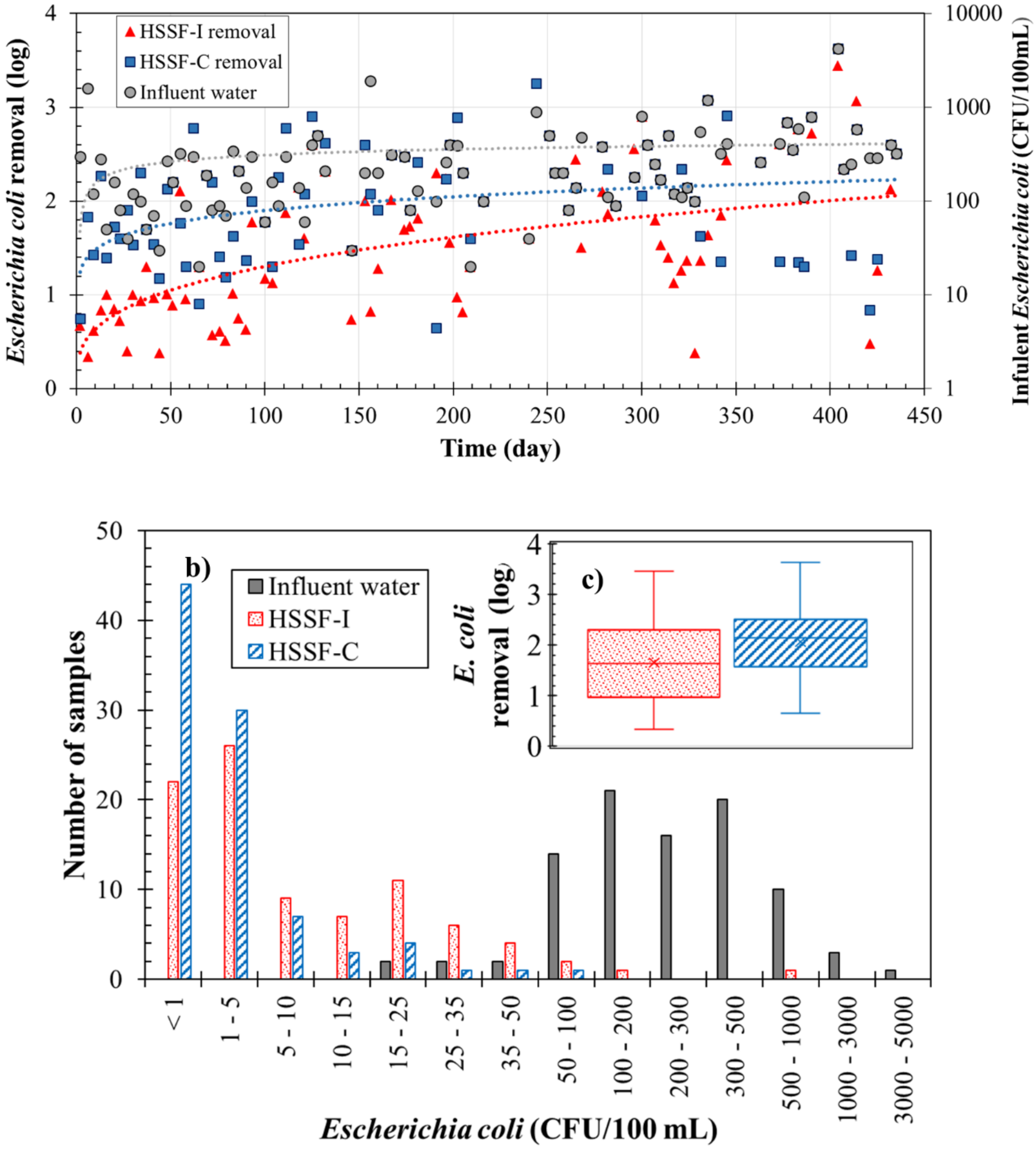

Figure 3 – a) *Escherichia coli* removal values over time of HSSF-I (intermittent) and HSSF-C (continuous); b) histogram of the *E. coli* frequency of the influent water and filtered waters from HSSF-I and HSSF-C, c) box-plot graph showing the removal data by the HSSF-I and HSSF-C.

Statistical analysis indicated a significant difference between the *E. coli* removal values from HSSF-I and HSSF-C ($p < 0.001$, Mann-Whitney test). Therefore, HSSF-C was more effective for *E. coli* removal, and the flow regime was decisive to affect the bacteria removal in a long-term surface water treatment.

Our result was similar to those with HSSF fed by other supply water, greywater, and treated wastewater for up to 374 days (Young-Rojanschi and Madramootoo, 2014; Verma et al., 2017; Maciel and Sabogal-Paz, 2020; Andreoli and Sabogal-Paz, 2020; Shaikh and Ahammed, 2021) but different from the two studies with HSSF treating surface water in the short-term (up to 48 days), which produced statistically equal *E. coli* removal values between HSSF-I and HSSF-C (Fava et al., 2022; Lubarsky et al., 2022). Thus, at the beginning of the operation, there seem to be no differences between both flow regimes, but in a long-term operation, there are decisive changes for the development of a more robust and even more favorable biological layer for HSSF-C, as also pointed out by Lamon et al. (2021) in 8 months of HSSF operation. *Schmutzdecke*'s development is related not only to the influent water quality but also to clogging by suspended particles, the microorganisms attached to the sand layer (Fava et al., 2022), and the MRF (Maciel and Sabogal-Paz, 2020).

Bivariate analyses were applied to better understand the *E. coli* removal values and *schmutzdecke* development in the HSSF-I and HSSF-C (Table 5).

Table 5 – Spearman's correlation coefficient (r) between *E. coli* removals values from HSSF-I (intermittent) and HSSF-C (continuous) with HSSF operating parameters.

	Influent water	**Operating time**	**Ripening time**
HSSF-I	0.495*	0.562*	0.095
HSSF-C	0.532*	0.318*	- 0.004

Notes: * indicates a correlation (p-values < 0.05).

Ripening time is the time when filter production < 48 L d^{-1}.

The results indicated positive correlations of *E. coli* removal values with influent water and operating time, in two different grades of correlation: weak (0.2 < r < 0.39) and moderate (0.40 < r < 0.59). *E. coli* removal values in HSSF-I were moderately correlated with operating time and influent water, while HSSF-C was only moderately correlated with influent water. There were no strong correlations (0.60 < r < 0.79), nor correlations between *E. coli* removal values and ripening time (p = 0.378 for HSSF-I and p = 0.973 for HSSF-C).

For both HSSFs, natural fluctuations in surface water quality significantly affected the *E. coli* removal efficiencies, and this translated into the high or low peaks (Figure 3) without necessarily indicating an increase or decrease in filter efficiencies. Once again, the quality of the influent water proved to be one of the most decisive factors for the performance of HSSFs when used for surface water treatment.

Due to these large variations in influent water, we could not clearly visualize the biological layer ripening in Figure 3, given by the progressive increase in efficiency during a filter run (Elliott et al., 2008), nor indicate it by the correlation analyses. However, as the HSSFs were treating a complex matrix with high microbiology risk, some biological layer development was expected during these 430 days of operation.

The HSSF ripening was indirectly inferred by the correlation analysis between the operating time and *E. coli* removal efficiency (Table 5) and by the sharp trend line in Figure 3a. Both indicated increases in efficiency throughout the operation, even with natural variations and maintenance activities. The latter caused only slight increases in *E. coli* in HSSF-I (41 ± 97 CFU/100 mL) and HSSF-C (6 ± 9 CFU/100mL) effluents.

According to the trend line, the HSSF-C reached an average 2 log of *E. coli* removal value after 150 days of operation, while the HSSF-I only reached after 400 days. Besides the effect of MRF on *E. coli* removal values, we suppose that smaller MRFs of HSSF-C forced *schmutzdecke* microorganisms to greater depths than HSSF-I, which would also explain its faster recovery after maintenance activities (Maciel and Sabogal-Paz, 2020; Terin et al., 2022).

3.1.3. Protozoa

Giardia spp. cysts and *Cryptosporidium* spp. oocysts in HSSF-I and HSFS-C filtered water samples are shown in Figure 4. HSSF-I removed 2.89 (± 0.32) log of cysts and 0.95 (± 0.45) log of oocysts, while HSSF-C reached more than >3 log of cysts and 1.22 (± 0.10) log of oocysts. The protozoa removal values obtained by both HSSFs are in accordance with the ranges reported in the HSSF literature, which are from 1 to > 5 log for cysts and from 0.44 to 4 log for oocysts (Freitas et al., 2022).

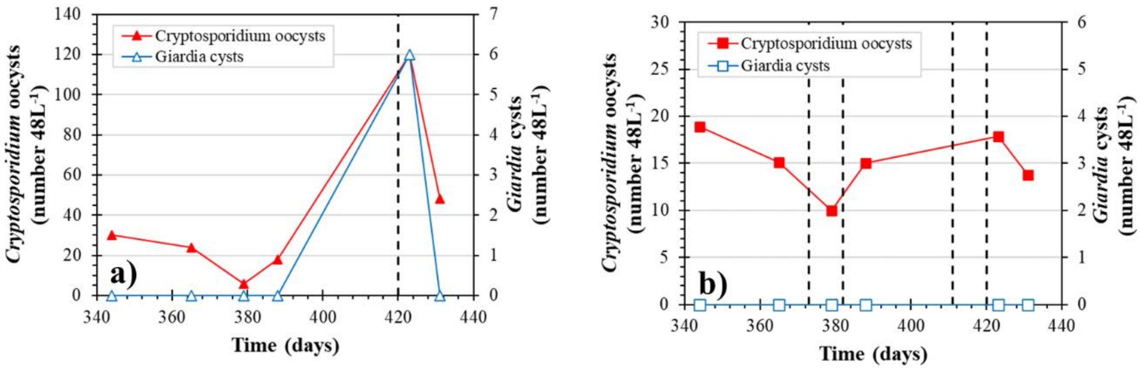

Figure 4 – Cryptosporidium oocysts and giardia cysts in water filtered by a) HSSF-I (intermittent) and b) HSSF-C (continuous). Vertical dashed lines indicate maintenance activities.

Regardless of the flow regime, HSSF achieved higher removals of *Giardia* spp. cysts than *Cryptosporidium* spp. oocysts ($p < 0.0001$, Mann-Whitney test), however this was not related to the filter itself, but to the characteristics of the encysted forms.

Oocysts can compress themselves and are smaller than cysts (i.e., 4-7 µm versus 8-12 µm of cysts), therefore they pass more easily through sand pores (USEPA, 2012). Therefore, in addition to being the protozoan indicator and causing diseases if consumed, *Cryptosporidium* oocyst is also challenging for household water treatment.

HSSF-C showed higher removal values for both protozoa, including the complete removal of *Giardia* spp. cysts during the 106 days of inoculation. The HSSF-C kept its efficiency even after 4 maintenance activities (Figure 4b), while the HSSF-I was cleaned only once (420 days of operation) and that was enough to significantly increase the pass-through of cysts and oocysts (Figure 4a). At that time, 120 oocysts and 6 cysts passed through the sand pores. The development of a more stable biological layer in a long-term operation, associated with a low MRF and the adherence and transport mechanisms, may explain the better results of HSSF-C.

Andreoli and Sabogal-Paz (2020) warned that oocysts and cysts pass not only through HSSF-I but also through HSSF-C, when applied to nutrient-poor groundwater treatment. Therefore, the surface water feeding may have also favoured the development of more complex and diverse biological layers, which increases the retention of protozoa in the *schmutzdecke*, including reaching maximum values in the HSSF-C.

3.1.4. DO profile

Figure 5 shows DO profiles for each HSSF model. High standard deviations for DO concentration were observed because samples were collected at different stages of biological development (during 430 days) within the filters.

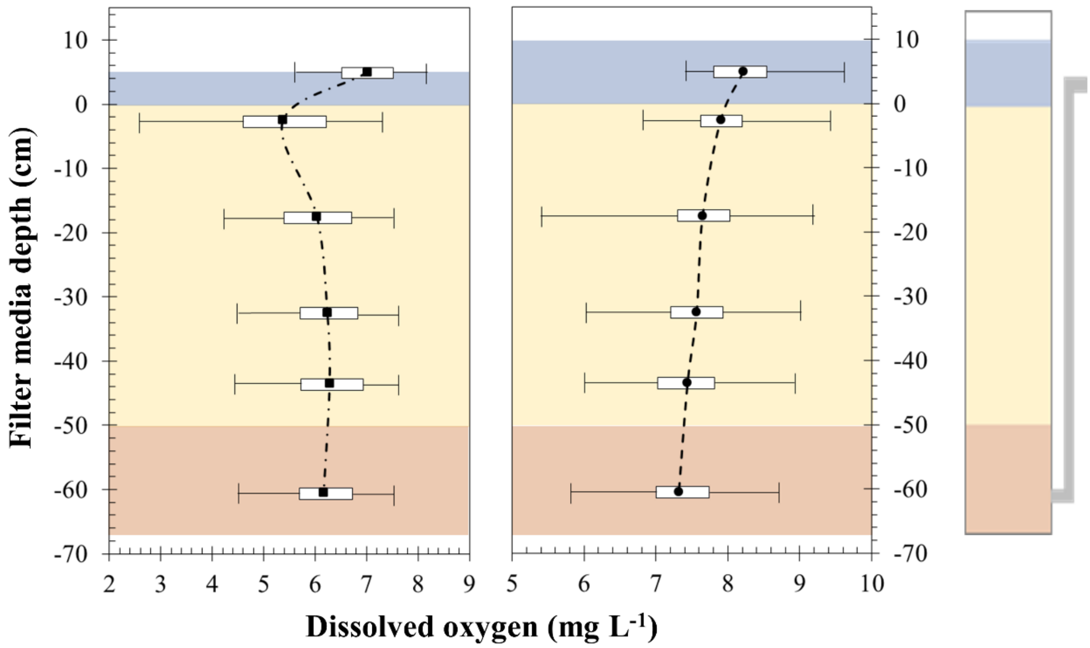

Figure 5 – DO profiles in a) HSSF-I and b) HSSF-C. The blue background is the water layer, the yellow background is the sand media layer, and the brown background is the drainage layer. Standard deviation bars refer to the temporal deviations and the 0 cm represents the media top.

HSSF-I showed a sharper decline in DO concentration in the first centimetres of filter media, with a slight consumption along the filter bed; while HSSF-C presented a progressive decrease of DO concentration with the increase of depth. In the HSSF-I, a portion of the fed volume stayed in contact with the *schmutzdecke* for approximately 12h (pause period), causing a higher DO consumption between sample ports 1 and 2. On the other hand, in HSSF-C, the water slowly passed through the *schmutzdecke* region and ran by the filter media at the same rate, producing progressive DO consumption with the bed length. These profile tendencies converged with the measures of Young-Rojanschi and Madramootoo (2014).

Higher DO concentrations in samples 5 cm above the filtration media than in samples taken from within the filtration media ($p < 0.05$, Mann-Whitney test) indicate that microbiological activity took place throughout all filter beds, more extensively at the top layers. In general, DO concentrations in samples from sampling ports 1 and 2 presented a significant difference between each other and the rest of the samples ($p < 0.05$, Mann-Whitney test), while samples from lower sampling ports (3, 4, 5, and 6) had similar DO concentration between each other.

Our results indicate significant biological activities at greater depths, between 2.5 and 17.5 cm, as well as the first 2.5 cm already described in the HSSF literature (Freitas et al., 2022). Microbial removals suggest that there is a greater depth of active biological layer in HSSF-C than in HSSF-I, however, more studies should be performed to clearly confirm how much it is. At these different depths, different microbial compositions are expected (Wang et al., 2014).

3.1.5. Other water quality parameters

We also evaluated other water quality parameters in this long-term surface water treatment. Statistical tests indicated a significant difference ($p > 0.05$) between the filtered water quality after the HSSF-I and HSSF-C in terms of DOC, DO, pH, and apparent color values, and a significant equality ($p < 0.05$) in relation to electrical conductivity, absorbance 254 nm, true color, and particle size values. Results indicated that, even with some efficiency similarities, the two feeding strategies produce filtered water with different qualities for most parameters.

Regarding the significant differences, HSSF-I caused more variations in DOC and DO values, while HSSF-C caused more variations in pH and apparent color values. Despite this, DOC, OD, and pH values of influent water and both filtered water ranged up to 15%, 5% and 2%, respectively, very small values that did not implied in a better or worse filter treatment model. On the other hand, apparent color removal values were much higher and equal to 72 (± 18)% after HSSF-I and 75 (± 22)% after HSSF-C.

3.2. Qualitative data analysis

3.2.1. HSSF construction

The HSSF construction was simple and required only two days of work by two people due to the ease of acquiring materials in São Carlos in Brazil and the builders' experience in handling materials and equipment for plumbing-sanitary services. The granular materials suitability was the step that required the most time and manual effort from the builders. To fill out an HSSF, 35 kg of fine sand, 25 of coarse sand, 11 kg of fine gravel and 4 kg of gravel were used. It required at least 13 h of work by two people to fit all materials, in which 4 h was for washing, 6 h for drying (if it was a sunny day), and 3 h for sieving.

Despite using similar HSSFs, the two supply systems (i.e., intermittent and continuous flows) produced different treatment systems in terms of ease of construction, size and cost. The intermittent feeding system consists of a perforated bucket attached to a float, therefore users with limited experience can easily build it with a drill and some glue. On the other hand, the continuous gravity-fed system uses a reservoir elevated by a metallic support, coupled to several hydraulic components, such as adapters, tubes and valves. In addition to more components, the continuous system also requires greater experience from the builder, as well as more space in the home (1.0 for HSSF-C versus 0.1 m^2 for HSSF-I) (Sabogal-Paz et al., 2020).

Considering our scenario with qualified professionals and availability of materials and equipment for construction, an HSSF-I cost US$ 86, while an HSSF-C cost more than twice that, US$ 194 (dollar exchange rate on January 30, 2023), due to the unit for its continuous supply. These costs were based on the Brazilian market and may differ in other markets. For the sake of comparison, the Biosand Filter concrete costs (HSFS model patented by CAWST) were estimated at US$ 60 (CAWST, 2012). Therefore, our Defofo HSSF is safe for water supply systems, but with financial and constructive counterpoints. In these cases, subsidies by governmental or non-governmental organizations are substantial for the water supply in isolated and vulnerable communities; especially for low-income areas that may have a significant percentage of their income compromised due to this treatment system.

3.2.2. HSSF operational challenges

HSSF-I requires a simple and easy operation; however, the manual effort to feed the HSSF-I is a matter of concern, especially for women, the elderly, children, and people with disabilities. This feeding bucket is heavy (~16 kg) and needs to be poured from 1 meter high, therefore, it requires manual effort that can be a limiting factor for the operation. On the other hand, HSSF-C requires a more complex operation, due to frequent flow adjustments for MRF control. Users need to be trained on how the HSSF-C works, as well as the importance of operating it at a constant flow rate. In this case, the user must have certain technical knowledge and time available for filter operations.

Another highlight is the estimated time to produce a water batch. At the beginning of the HSSF-I operation, the user waited about 48 min to produce 16 L of water, but due to the particle retention and filtration rate decay, at the end of the operation, this increased to 161 min. HSSF-C kept 16 L production time to 480 minutes.

HSSF-C required many more maintenance activities for surface water treatment than HSSF-I. For instance, at seasons with greater input of particles in surface water, the HSSF-C required maintenance up to once a week, unlike the 30 days reported in the literature (CAWST, 2012). This cleaning frequency must be optimized to make HSSF increasingly practicable and accessible, especially in long-term operation scenarios. Furthermore, in maintenance activities, there is direct contact between the users and a high concentration of microorganisms, mostly pathogens, which can be an imminent possibility of contamination. So, the environmental importance is another point that must be included in education, training, and monitoring programs for the target user.

4. Conclusions

- HSSF alone for surface water treatment is still not enough for consumption standards, as none of the models (HSSF-I and HSSF-C) produced safe water according to WHO standards (i.e., absence of bacteria and protozoa and turbidity < 1 NTU; WHO, 2017).
- The HSSF-I was more dependent on the operational parameters (influent water quality, operating time and ripening time) than HSSF-C for long-term surface water treatment.
- HSSF-C was more stable and efficient to remove turbidity, bacteria, and protozoa from surface water than HSSF-I, therefore it may be a more viable model for treating polluted water, but still needs field experiences to assess its user acceptability.
- Both feeding strategies required a pre-treatment to reduce the particle load in the influent water and a post-treatment to reduce the remaining microbiological risk. Therefore, multi-barrier household systems are encouraged for surface water treatment.

Credit author statement

Conceptualization: BLSF, UCT, LPSP. Data curation: BLSF, UCT. Formal analysis: BLSF, UCT, LPSP. Methodology: BLSF, UCT, LPSP. Funding acquisition, project administration, resources and supervision: LPSP. Writing – original draft: BLSF, LPSP. Writing – review & editing: BLSF, LPSP.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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