Pretreatment using *Opuntia cochenillifera* followed by household slow sand filters: technological alternatives for supplying isolated communities

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Pretreatment using *Opuntia cochenillifera* followed by household slow sand filters: technological alternatives for supplying isolated communities

Household Slow Sand Filter (HSSF) performance in continuous and intermittent flows was evaluated when influent water was treated with a natural coagulant extracted from *Opuntia cochenillifera*. The water under study, used as influent, had a turbidity of 111 ± 17.3 NTU. When clarifying the water with *O. cochenillifera*, the best condition obtained was 30 $mg.L^{-1}$ in natural pH (without correction), generating clarified water with turbidity satisfactory to filters operation (7.83 ± 2.32 NTU). The results indicated a better performance of continuous flow HSSF in turbidity removal (79.2% ± 8.39%) and higher efficiency of intermittent flow HSSF in the removal of *E. coli* (2.86 log ± 0.79 log for 12 h pause period and 2.41 log ± 0.42 log for 4 h pause period). For the sake of comparison, the evaluated HSSFs had the same production (60 $L.day^{-1}$). The impact on the interruption of the 96-h feed into the HSSFs was analysed and the results indicated a significant change in the quality of the filtered water after resuming the operation. This fragility of technology must be considered when it is implemented as lack of water can be a reality in the target communities. Acute toxicological assays with *C. xanthus* larvae showed no toxicity for pretreated and filtered water; however, more testing should be performed.

Keywords: safe water, biosand filters, coagulation, isolated communities, decentralized treatment

Introduction

According to the World Health Organization, in 2015, approximately 2.3 billion people did not have proper sanitation conditions and 884 million people had no access to drinking water supplies [1]. This lack can particularly be seen in isolated communities such as low-income populations, small towns, rural areas and in the outskirts of urban centres.

For these isolated communities, the WHO recommends using decentralized water treatment technologies [2]. This type of technology enables users to treat household water, thereby ensuring the safety of their own drinking water [3]. One such technology is the household slow sand filter (HSSF), a conventional slow filter adaptation that is efficient, easy to use, operate and maintain, and is inexpensive.

Due to their slow filtration mechanism, HSSFs also have limitations that are similar to conventional slow filters when removing solids and organic compounds, which makes influent water turbidity an important point when operating the units [4]. The excess of suspended material in the incoming water obstructs the intergranular voids causing a reduction in the filter run and an increase in the frequency of cleaning. Therefore, if influent water has high values of turbidity, clarification is essential before insertion into the filters.

Using traditional coagulants (e.g. aluminium or iron salts) is common in water treatment plants - WTPs around the world. Although efficient in clarifying water, these coagulants can be expensive, cause adverse health effects and generate large volumes of non-biodegradable sludge making it difficult to dispose of them in the environment [5]. In isolated communities, an alternative to clarifying water may be by using natural coagulants extracted from plants [6].

Opuntia cactus as a natural coagulant may be an attractive solution for turbidity removal [7,8]. According to Miller et al [7], coagulant extracted from *Opuntia* spp. cladodes can reduce turbidity up to 92%. However, selecting the best natural coagulant should also be linked to its local availability. One of the most common *Opuntia* spp. species in Latin American countries, especially in Brazil, is *Opuntia cochenillifera*, which is used for cooking, and feeding animals, e.g. cattle [9]. This accessibility indicates the potential for coagulant extraction at a local level (i.e. isolated communities).

HSSFs were developed to be operated intermittently [10]. This design gives freedom for the user to produce water according to their need. Intermittent flow operation is achieved by daily batch feeding; however, some changes were made at the filter outlet, which maintains a constant minimum water level at the top of the filter bed (stationary level). This operation condition generates the so-called pause period - the time needed for physical-chemical and microbiological processes acting on the *schmutzdecke,* which can treat the water. Huisam and Wood [11] describe the *schmutzdecke* region as the interface between top sand and water, which accumulates retained material and intense microorganism activity.

According to CAWST [4], the water to be treated should be kept for a pause period of 1 to 48 h in the filter media pores between each batch operation, however Young-Rojanschi and Madramootoo [12] found that this time could be increased to 72 h without major changes in the filtered water quality. Likewise, Jenkins et al. [13] found that the increase in the pause period might raise the filter efficiency.

Although they are commonly operated in intermittent flow, HSSFs can also be operated either by pumping or by gravity, similarly to conventional slow filters.

Young-Rojanschi and Madramootoo [14] evaluated two filters, one intermittent and the other continuous by pumping, with the same capacity of daily filtered water. The influent water to the filters was taken daily from Lake Saint-Louis (Montreal, Quebec) and stored in reservoirs for 24 hours for particle sedimentation. The authors observed higher turbidity (96% ± 3% versus 87% ± 7%) and *E. coli* (3.71 log ± 0.59 log versus 1.67 log ± 0.51 log) efficiencies when operated continuously.

In this context, Maciel and Sabogal-Paz [15] observed that water level control helped the operational conditions in HSSF. In the continuous flow, the float helped to mature the filter more quickly and, together with a non-woven blanket, extended the filter runs in the intermittent flow. HSSFs with a water level control were also efficient to remove *Microcystis aeruginosa* and microcystin-LR [16].

Generally, the configuration of the intermittent flow HSSF reduces electrical energy dependence required by continuous operation; however, the daily variation of the hydraulic load caused by the intermittent feed can affect the composition and efficiency of the biofilm and, consequently, the efficiency of the treatment. On the other hand, the HSSF in continuous flow does not have this drawback, nevertheless it requires more space in the household and it is not user friendly due to the need for a constant filtration rate. These advantages and disadvantages should be weighed up according to the reality of the community at the time of technology transfer.

Similar to conventional filters, household filters must be cleaned when they achieve the end of the filter run. However, unlike the conventional ones, the design of the HSSF makes it possible to clean without having to remove and replace the filter sand [10]. In addition to the benefits of the design, maintenance can be facilitated by installing blankets on the top of the filter media [15]. By attaching the blanket to the filter, it will retain some of the impurities and consequently make it easier to maintain as it can be easily removed, washed and replaced in the unit.

In this context, this paper presents the results obtained by operating two HSSFs, continuous and intermittent flows, using a non-woven blanket (felt) installed at the top of the filter media together with the pretreatment of influent water with coagulant powder extracted from *O. cochenillifera*. The innovation of this research is the pretreatment of the water with high turbidity through coagulant of easy access and subsequent use of HSSF in different operation modes.

The aims of this study were: i) flow characterization in two HSSFs by tracer tests; ii) influent pretreatment evaluation with a natural coagulant powder extracted from *O. cochenillifera*; iii) HSSF performance after pretreatment; iv) impact on each HSSF caused by interrupting the feeding for 96-h in terms of turbidity and *E. coli* reduction; and v) toxicity evaluation of the pretreated water and filtered water by toxicological assays performed with *Chironomus xanthus* larvae.

Materials and methods

HSSF Construction

The HSSF in the present study was based on CAWST [4], however the material used in the structure was different because concrete can be highly complex when assembling, transporting and finding commercial parts. Therefore, the HSSF was built using PVC tubes and fittings available in Brazilian isolated communities. The PVC materials used comply with Brazilian legislation, NBR 5648 [17], in terms of quality for water distribution in residential plumbing; however, this standard does not include volatile organic compounds (VOCs). It should be noted that Skjevrak et al. [18] detected few VOCs migrating from PVC pipes into drinking water. This fact indicates the need of detailed studies, such as toxicity tests for filtered water.

Filter media was selected from materials easily found in hardware stores, such as sand (fine and coarse) and gravel (fine and coarse). However, before inserting them into the filter body, the materials underwent three procedures to adjust the granulometry and ensure the best filtration condition.

Filter materials were washed in water extracted from the well at the São Carlos School of Engineering at the University of São Paulo (SCSE/USP). This manual procedure was repeated until the water was visually clean (turbidity ± 15 NTU). The fine and coarse gravel were washed and disinfected with 0.5% sodium hypochlorite for 48 h; afterwards, the materials were exposed to the sun to remove the moisture. After drying, the filter materials were sieved using sieves commonly found in Brazilian isolated communities, according to Table 1.

[Table 1 near here]

After preparation, a fine sand sample was submitted to the granulometric test indicated in ISO 14688-2 [19]. By analysing the grain size curve, the D_{10}, D_{60} and the uniformity coefficient (UC) were found.

Filter materials were introduced into the filter body carefully so that there was a homogeneous distribution of each material in its layer. When inserting the fine sand, the filter was prefilled with water to prevent pockets of air from forming along the filter media and to allow stratification of the material as well.

A non-woven filter blanket (0.2 g.cm^{-3} of specific mass, 100% polyester, and 2.0 mm of thickness) was placed at the top of the fine sand. Due to the tendency to float, the blanket was attached to the top of the filter layer with a PVC ring that had a diameter smaller than the inside diameter of the filter body.

After assembling, the filters were operated in continuous and intermittent flows (Figure 1). For the sake of comparison, both had a production of 60 $L.day^{-1}$.

[Figure 1 near here]

In intermittent flow operation (Figure 1a), the unit was fed with manually clarified water. The feed volume per batch was 15 L (equivalent to the volume occupied by the water inside the unit). When fed, the water level and filtration rate (maximum of 2.79 $m^3.m^{-2}.day^{-1}$) were controlled by float and, over time, the level dropped to zero the filtration rate.

In a continuous flow operation (Figure 1b), the unit was fed by a 100 L water tank positioned 1.10 m from the floor. In this operation, the water level and filtration rate were constant. The water level was controlled by float, so that the water depth was constant (± 10 cm) and the filtration rate was adjusted to 1.22 $m^3.m^{-2}.day^{-1}$ per valve installed at the filter outlet.

Tracer tests

A solution of 100 mg of $NaCl.L^{-1}$ was used as a tracer in a step injection, in triplicate. To construct the tracer concentration curves over time (C x t) a conductivity probe (with *Go! Link* interface) was installed at the filter outlet. The conductivity probe was calibrated with NaCl standard solution and the measurements were converted to sodium chloride concentration. Data was processed using Excel® and Origin 8.6® software.

Continuous flow characterization was done by constructing the Residence Time Distribution (RTD) curve, following the methodology proposed by Levenspiel [20]. Based on this, information was collected about the residence time and if the system was behaving as the extremes of flow ideality (complete mixing or plug flow). This analysis was carried out using three uniparametric models: small and large dispersion models and tanks-in-series model.

The intermittent flow analysis was based on the Morrill Dispersion Index (MDI) cited by Lynn et al. [21], which correlates the tracer output concentration as a function of void volume.

Preparation of influent water to filters

The water under study was prepared by stirring 200 L of water from the SCSE/USP well with kaolinite (Fluka-Sigma Aldrich®), humic acid (Sigma Aldrich®) and *E. coli* culture (ATCC 11229, purchased from the *André Tosello Foundation* - Campinas, SP, Brazil) aiming to obtain, respectively, turbidity ± 100 NTU, true colour ± 30 HU and *E. coli* of ± 1000 CFU.100mL^{-1}. This water imitates a source with a microbiological risk and high turbidity, characteristics similar to numerous sources in Brazil [22].

Slow filtration does not support water with high turbidity; therefore the influent water has to be pretreated prior to insertion into the filters. Pretreatment was carried out using a natural coagulant powder extracted from *O. cochenillifera* following the procedures described in Miller et al. [7] and Shilpa et al. [8]. Consequently, our study aimed at evaluating the HSSF operation when the influent water had high turbidity values.

Treatability assays in jar tests were performed to optimize the parameters associated to the treatment. The results obtained from the laboratory were adapted to a system on a larger scale capable of producing enough clarified water for the filter demand. The system in question consisted of two reservoirs (R1 = 200 L and R2 = 50 L) and a mechanical stirrer (CETEC®, model M.CM200), according to Figure 2.

[Figure 2 near here]

In R1, the water under study was prepared with kaolinite, humic acid and *E. coli*. Then, in the same reservoir, the coagulant powder was inserted to allow for pretreatment of the water under study. The clarified water produced was transferred to R2 by tap. As shown in Figure 2, the lid of R2 was replaced by a tea towel aiming to eliminate suspended flakes generated in the pretreatment.

An aquarium submersible pump (ALEAS®, model HM-5063) was placed inside R2 to transport the clarified water daily to the raised reservoir at 8 am every morning. In addition to feeding the continuous flow HSSF, the raised reservoir was also used to store the water for feeding the intermittent flow HSSF that took place at 8 am, 12 pm, 4 pm and 8 pm. In order for the quality of clarified water to remain constant throughout the day, another aquarium submersible pump was placed in the raised reservoir; however, in this case, the pump was only used to homogenize the water. It should be mentioned that using a mechanical stirrer might not be sustainable in isolated communities. However, the aim of this study was to evaluate the performance of pretreatment HSSFs, and in other studies, adaptations to the operation should be implemented in order to make pretreatment feasible.

Measurements and Sampling

Influent, clarified and filtered water samples were collected in 500 mL plastic bottles. Influent sampling was carried out immediately after preparation. Sampling of the clarified water was also done immediately, however it was performed after the liquid had passed through the tea towel attached to R2. Filtered water from the continuous flow HSSF was analysed in a timely manner at the time determined by the hydrodynamic assay. Filtered water of the intermittent flow HSSF was analysed in two ways: i) filtered water collected at 8 am referring to the 12-hour pause period (8 pm the previous day until 8 am the following day); and ii) the composite sample with filtered water at 12 pm, 4 pm and 8 pm, referring to the 4 h pause periods.

The samples were analysed for turbidity, apparent colour, true colour, pH, alkalinity, temperature, zeta potential and *E. coli*, following the methodology described in APHA et al. [23] during the 75 days of operation. Filtered water quality parameters were compared to the Brazilian requirements of Consolidation Ordinance No. 5 [24] and the World Health Organization [25] to evaluate the performance of HSSFs.

Maintenance

HSSF was cleaned when the filtration rate did not remain constant at 1.22 $m^3.m^{-2}.day^{-1}$, when the output valve was fully open. The intermittent flow HSSF was cleaned when it was not possible to insert the feed volume (15 L) into the tank coupled above the filter. In these cases, three simple maintenance procedures were carried out in the HSSFs: i) scraping the blanket with a spatula, ii) cleaning the blanket with water from the SCSE/USP well, and iii) draining the impurities in the filter using a tea towel.

Toxicological tests

Toxicological assays were performed to investigate acute toxicity caused by the natural coagulant (*O. cochenillifera*) and by the filter materials. Influent, pretreated and filtered water were evaluated. Tests were carried out in triplicate (with each type of water) with the blank test (distilled water). In each trial, six *C. xanthus* IV instar larvae were exposed to 250 mL of sample for 96-h without aeration. Afterwards, the number of live larvae was counted.

Blanket Scanning Electron Microscopy

Non-woven blanket placed on the top of the filter layer were analysed before and after the operation, according to Scanning Electron Microscopy (SEM) photomicrographs at 500x magnification.

Statistical analysis

Hypothesis F tests by ANOVA (5% level of significance) were applied to evaluate the performance of the units.

Results and Discussion

HSSF Construction

The CAWST model built on concrete demands effort and specific tools for construction [4]; in addition, it is heavy and may present leaks [26]. The PVC model did not use complex tools and the materials were found easily; however, it was US$ 60 more expensive than the concrete model. It should be noted that the CAWST model needs specific tools, which can reach US$ 1000 [15].

Characteristics of the filter material

The D_{10} and the UC of the fine sand were 0.15 mm and 1.68, respectively - values within the range recommended by CAWST [27].

Tracer tests

The tests for the characterization of the intermittent and continuous flows can be seen in Figure 3.

[Figure 3 near here]

The mean residence time was 350 (± 22) min in the continuous flow system. This fact was decisive in estimating the sampling time of the filtered samples to evaluate the daily efficiency of the system. In the continuous flow filter, the uniparametric model that matched the experimental data best, according to the Pearson correlation (r^2), was the tanks-in-series model. Using this model for the experimental data resulted in 11 ± 8 numbers of reactors in series, which is a reality close to the plug flow, according to Levenspiel [20].

In the intermittent flow filter, three feeds were required using water to remove the entire dose from the tracer. The tailing formation after the second feed volume until the end of the assay can be explained by the pore diffusion phenomenon of the filter material discussed by Jimenez et al. [28]. The modified MDI index for this system was 1.50 (± 0.04), characterized as a system close to the reality plug flow, according to Tchobanoglous et al. [29]. Plug flow characteristic for both filters favour the performance of biological processes [30], which potentiate the HSSF efficiency.

Pretreatment with O. cochenillifera

The optimal condition for turbidity removal in treatability assays was the *O. cochenillifera* dosage = 30 $mg.L^{-1}$, pH = 6.8, rapid mixing gradient = 250 s^{-1}, rapid mixing time = 60 s, slow mixing gradient = 25 s^{-1}, slow mixing time = 20 min and settling velocity = 0.25 $cm.min^{-1}$, providing clarified water turbidity of 4.44 NTU, lower than that recommended by CAWST [4].

The results obtained from the jar tests were transferred to the larger scale system (Figure 2). However, in the slow mixing step, there was a need to change the rotation obtained in the laboratory due to the limitation of the mechanical mixer at 200 rpm (83 s^{-1}). This change directly affected the slow mixing gradient and, consequently, the efficiency of the pretreatment. To overcome this shortcoming, the settling time was fixed at 24 h, a sufficient range to obtain clarified water with turbidity < 10 NTU. The performance of this adapted pretreatment on a larger scale can be seen in Table 2.

[Table 2 near here]

As expected, the transfer of the fast and slow mixing parameters to a larger scale system reduced the turbidity removal efficiency. However, scaling adaptations in pretreatment still provided conditions for obtaining clarified water with turbidity lower than that recommended by CAWST [4] for the HSSF influent. The potential of the coagulant was 92.7% ± 2.81, producing clarified water turbidity of 7.83 ± 2.32 NTU. Within this framework, *Moringa oleifera* (another plant used as a natural coagulant) was evaluated on a bench scale. Results showed turbidity removal efficiency when it was used as a pretreatment for solar disinfection [31], hence other plants have the potential to be used as a pretreatment for HSSF.

The pretreatment had efficiencies of 73.9% ± 4.48 for apparent colour and 11.7% ± 3.96 for true colour. Antillón et al. [32] observed greater removals for apparent colour (92%) when using the coagulant extracted from the mucilage of *O. cochenillifera* cladodes. Despite the higher efficiency, mucilage as a coagulant can vary the performance depending on the part of the vegetable that is being used [7].

After clarification, a 10.3% increase in pH in water and 20.9% in total alkalinity was observed. The phenomenon may be related to the presence of carbonates in the composition of *Opuntia* spp., indicated in the X-ray diffractometry from Contreras-Padilla et al. [33].

The temperatures of water under study and clarified water varied between 21.8 and 26.8 °C. According to Zhang et al. [34], values close to 10°C could reduce the performance of *Opuntia* spp. in the water treatment. This is attributed to the lower degree of agitation of molecules and, consequently, less contact of the coagulant with the particles.

The zeta potential after coagulation remained negative and relatively constant, excluding the possibility of charge neutralization. Miller et al. [7] also detected this same tendency and, after carrying out an in-depth study, affirmed that the predominant coagulation mechanism was the adsorption and formation of bridging to *Opuntia* spp.

E. coli was not removed in the clarification. It is believed that by remaining in contact with the organic matter of the coagulant during the 24 h of sedimentation, conditions were created so that the added *E. coli* would grow in the water. Tassoula [35] found 0.3 log growth in distilled water with less than 3 mg.L^{-1} of dissolved organic carbon - a situation similar to that of the present study (Table 2).

Due to the presence of *E. coli,* it was not possible to test the water taste caused by the addition of natural coagulant. However, it is estimated that the taste will be not a problem in isolated communities because *Opuntia* spp. is used for culinary purposes [9].

HSSF operation

The performance of the HSSFs in turbidity removal is shown in Figure 4.

[Figure 4 near here]

Filtered water showed turbidity of 1.62 (± 0.59) NTU for a 12-hour pause period and 1.83 (± 0.80) NTU for a period of 4 h, thus a greater removal was observed (79.2 %

± 8.39 versus 77.1% ± 10.6) for the greater cited time. These results are equivalent to those found by other researchers [36, 37].

Jenkins et al. [13] also observed an influence of the increase in the pause period in the turbidity removal efficiency (95.4% in a pause period of 16 h versus 89.5% in a pause period of 5 h). It is a widely held view that the longest time favours the physical-chemical and microbiological processes within the intermittent HSSF. Turbidity removal obtained by Jenkins et al. [13] was slightly higher than the one found in our study, however from different influent water (a fact that explains the discrepancy).

In continuous flow HSSF, turbidity removal was 79.2% ± 8.39 (1.47 ± 0.40 NTU). The favourable result may be the reflection of a lower filtration rate when compared to the intermittent operation. This result is in line with the research conducted by Young-Rojanschi and Madramootoo [14], which also showed a better performance of continuous HSSF than intermittent HSSF (96% versus 87%).

The influence of a lack of feeding that occurred on the 21st, 28th, 33rd, 34th, 35th and 36th days of the operation was evaluated (Figure 4). These breaks in the operation were intentional to evaluate the filter resilience, because this situation can happen in homes, for example, during school holidays. According to the research conducted by Young-Rojanschi and Madramootoo [12], HSSFs withstand feeding intervals of up to 72 hours without changing the quality of the filtered water. This may explain why the absence of feeding on the 21st and 28th days of the operation did not affect the filtered water quality of the HSSFs in continuous flow and intermittent flow (Figure 4). However, when this period was exceeded, as was the case on the 33rd to 36th days, filtered water samples changed in quality with increases in turbidity values up to 2.2 times that lasted up to 14 days after resuming feeding. On the other hand, the continuous flow HSSF did not show this tendency. Therefore, it is estimated that intermittent flow HSSF operation is more sensitive to lack of feeding in relation to turbidity removal.

Filter runs for intermittent and continuous flow HSSFs were reached on the 53rd and 59th days of operation, respectively. When water was used with low nutrient concentrations, Maciel and Sabogal-Paz [15] observed a delay in the *schmutzdecke* developing from HSSFs. This result shows the favourable use of *O. cochenillifera* as a ripening accelerator agent for the biological layer in HSSF, as studied by Grebremichael et al. [38] with *Moringa oleifera*.

The filtered water turbidity did not meet the Brazilian drinking standard of 1.0 NTU [23] before maintenance. However, nine days after cleaning, the intermittent flow HSSF already presented turbid effluents up to 1.0 NTU. The same did not happen in the continuous flow HSSF, which, although always close to 1.0 NTU, did not reach the standard during the 75 days of operation. In spite of this, intermittent and continuous flow HSSFs were able to produce filtered water with turbidity below 5 NTU, as recommended by the World Health Organization [24] in all the days of operation (Figure 4).

The performance of the HSSFs was also monitored according to other water quality parameters (Table 3).

[Table 3 near here]

The filtered water samples of the continuous and intermittent flow HSSFs did not meet the Brazilian drinking standard [23] for apparent colour (<15 HU). The difference between the apparent colour values in the filtered samples was not significant (single factor ANOVA, p = 0.3969), showing that the type of operation and the pause period did not influence the performance of the HSSFs in relation to the removal of the parameter.

The high apparent colour value in the filtered water samples is associated with the true colour that practically did not reduce in the slow filter treatment (Table 3). This result was already expected because, as reported by Ellis and Wood [39], slow filtration is a process with low removal of humic substances.

The pH values of filtered water met the Brazilian standard (pH between 6.0 and 9.5). There was an increase in pH after filtration, which was also reported by Murphy et al. [40]; however, these authors attributed the phenomenon to the calcium carbonate leaching of the filters built in concrete. In filters constructed in PVC, the increase may have occurred due to the leaching of the filtering materials.

Total organic carbon was reduced in both filters (Table 3). Lynn et al. [21] attributed this performance to the biological layer formed on top of the filter layer.

E. coli removal from the HSSFs can be seen in Figure 5. In the units, there was a progressive increase in the *E. coli* removals during the operation, a tendency associated to the maturation of the biofilm [41].

[Figure 5 near here]

The intermittent flow HSSF after a 12-hour pause period obtained greater removals of *E. coli* than in a 4-hour pause period (2.86 log ± 0.92 log versus 2.41 log ± 0.81 log). This increase in efficiency in longer pause periods was also reported by Elliott et al. [41] (2.68 log ± 0.37 log for a 24-hour pause period and 2.55 log ± 0.33 log for a 12-hour pause period).

Mean values of *E. coli* reduction in the intermittent flow were closer than those obtained by Elliot et al. [41] and both studies had organic matter in the influent water, which likely favoured the biological layer developing. Other studies revealed lower *E. coli* reduction, between 1.15 log and 1.7 log [13, 21], however this influent water had a low organic matter level.

At the beginning of the operation, continuous HSSF had greater removal of *E. coli* than intermittent HSSF with a 4-hour pause period. The promising outcome for the continuous operation compared to the intermittent one was also described by Young-Rojanschi and Madramootoo [14] and Maciel and Sabogal-Paz [15]. However, the lack of feeding the HSSFs for 96 h affected the water quality of the continuous HSSF, making the removal of *E. coli* lower than that produced by the intermittent flow, after that period. Because of this, the mean removal of *E. coli* in continuous flow was 2.10 log ± 0.48 log, a lower value than that obtained by the intermittent HSSF. This phenomenon provides evidence of the fragility of continuous HSSF when there is no longer a water supply - an aspect that can occur in target communities. It should be noted that a 22.4% reduction in the removal efficiency of *E. coli* was also recorded in the intermittent HSSF, in the same period, with a 12-hour pause period (Figure 5).

Before the 96-h shutdown without feeding, the efficiency of the continuous flow HSSF was based on the development of the biofilm. The equilibrium of this film was a consequence of the low and constant feeding rate. When the operation was interrupted, it is believed that there was a change in the biofilm, which led to a consequent reduction of efficiency. This situation is not experienced by the intermittent HSSF that suffers from specific feeding. This feature of intermittent HSSF operation may have provided conditions for the growth of an adapted biofilm, favouring the resilience of the filter to the lack of feeding.

The maintenance performed on the 53rd and 59th days influenced the ability of the filters to remove *E. coli* (Figure 5), which was a situation that was expected. According to Maciel and Sabogal-Paz [15], the time after maintenance is the operational parameter with the highest correlation with the *E. coli* reduction. In our study, *E. coli* reduction was rapidly established after maintenance and it is believed that the organic matter load from the natural coagulant influenced this process.

It should be noted that only the samples on the 50th, 64th and 71st days of the intermittent HSSF, with a 12-hour pause period, showed absence of *E. coli*. After 50 days of operation, the intermittent filter already had maturation conditions; however, maintenance activities performed on the 53rd day affected its efficiency, and consequently, there was an absence of *E. coli* only on the 64th and 71st days. Nevertheless, it is essential to disinfect the filtered water afterwards.

Toxicological tests

Results from acute toxicological assays showed no *C. xanthus* larvae mortality in influent water, pretreated water with *O. cochenillifera* and filtered water (from continuous and intermittent HSSFs) indicating that there was no evidence of toxicity. However, tests with other test organisms for long periods (i.e., chronic assays) are still required to assess the safety of the filtered water.

Non-woven blanket (felt)

SEM photomicrographs of the blanket are shown in Figure 6. When new, the blanket has a fibrous structure with threads and no impurities adhered to the surface (Figure 6a). After 75 days of operation, these blankets were covered by impurities (Figures 6b and 6c). This retention in the blankets leads to longer filter runs [42], making it easier to maintain the filter, and opens up the possibility of reducing the thickness of the sand layer using higher filtration rates [43]; an advantageous situation in household filters because of the limited production of filtered water. At the end of the filter runs, the blankets were easily removed from the filter due to the PVC ring used in the attachment. This aspect is of particular importance in HSSFs because it provides relative simplicity in the cleaning process and reduces maintenance requirements.

[Figure 6 near here]

Conclusions

The 30 $mg.L^{-1}$ dosage of the natural coagulant without needing pH correction was sufficient to remove 92.7% ± 2.81 water turbidity, allowing the operation of the HSSFs; however, it was inefficient in reducing *E. coli*.

The intermittent HSSF with a longer pause period (12 h) presented greater turbidity removal (77.1% ± 10.6 versus 74.1% ± 13.0) and *E. coli* (2.86 ± 0.76 log versus 2.41 ± 0.42 log) when compared to the shortest pause period (4 h).

The continuous flow HSSF had higher turbidity removal efficiency, when compared to intermittent flow operation. However, the latter had a higher performance in *E. coli* removal.

Feeding interruption for up to 96 h affected the quality of the filtered water in turbidity and *E. coli* removals in the intermittent flow and continuous flow HSSFs, respectively.

Acute toxicological assays showed no *C. xanthus* larvae mortality indicating no water toxicity; however, more thorough tests are needed to evaluate the filtered water quality (i.e. VOC compounds).

The blanket retained some of the impurities and made it easier to operate the filters; therefore, it is recommended in HSSFs. Evidently, care must be taken to ensure that the blanket is properly fixed to the top of the filter media, as it tends to float.

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Declaration of interest statement

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

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Figure 1. Household Slow Sand Filter: (a) intermittent flow operation (maximum filtration rate of 2.79 $m^3.m^{-2}.day^{-1}$) and (b) continuous flow operation (constant filtration rate of 1.22 $m^3.m^{-2}.day^{-1}$). Units in centimetres.

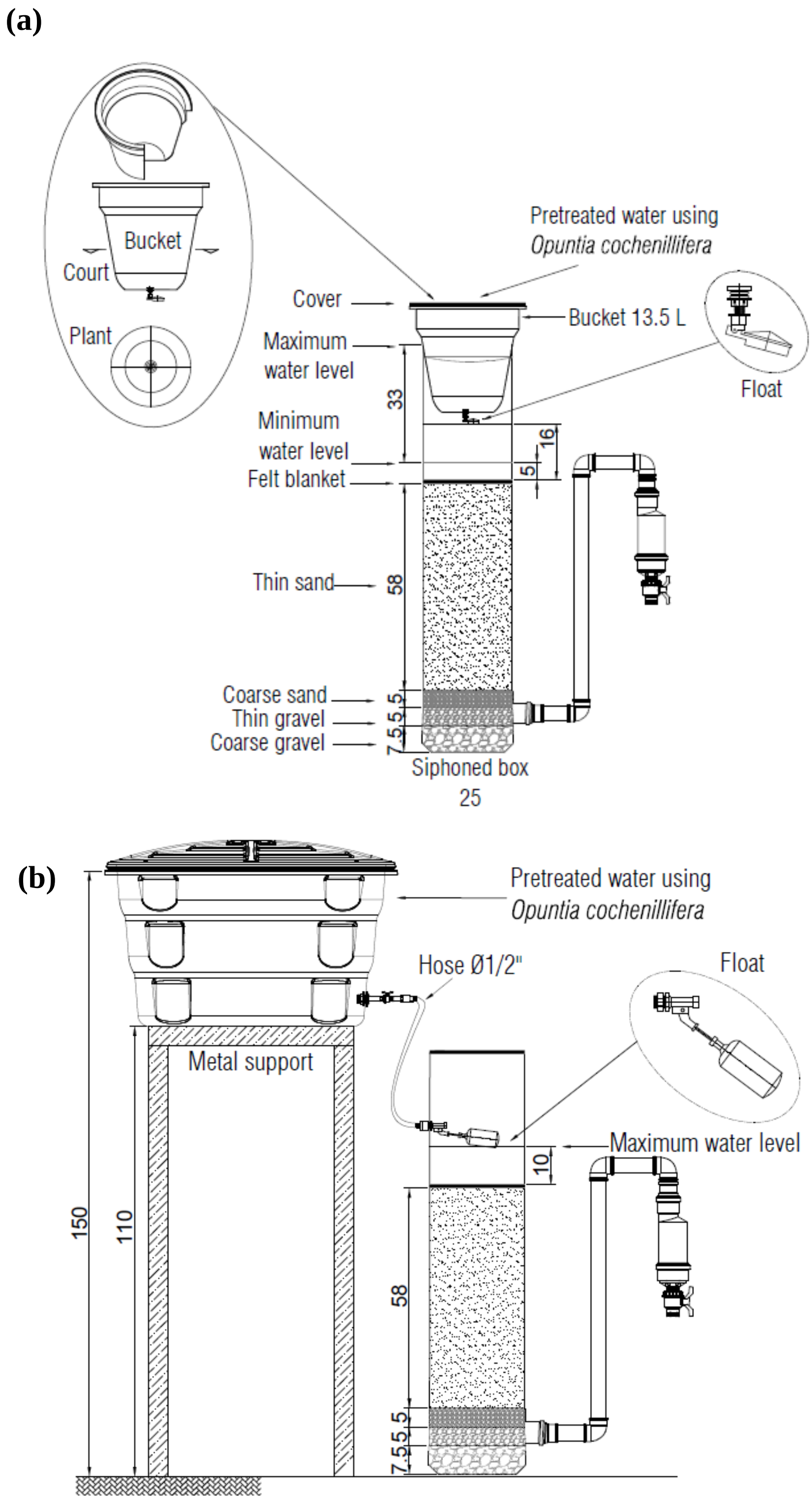

Figure 2. System with two reservoirs (R1 = 200 L and R2 = 50 L) adapted for the influent water pretreatment of the household slow sand filters.

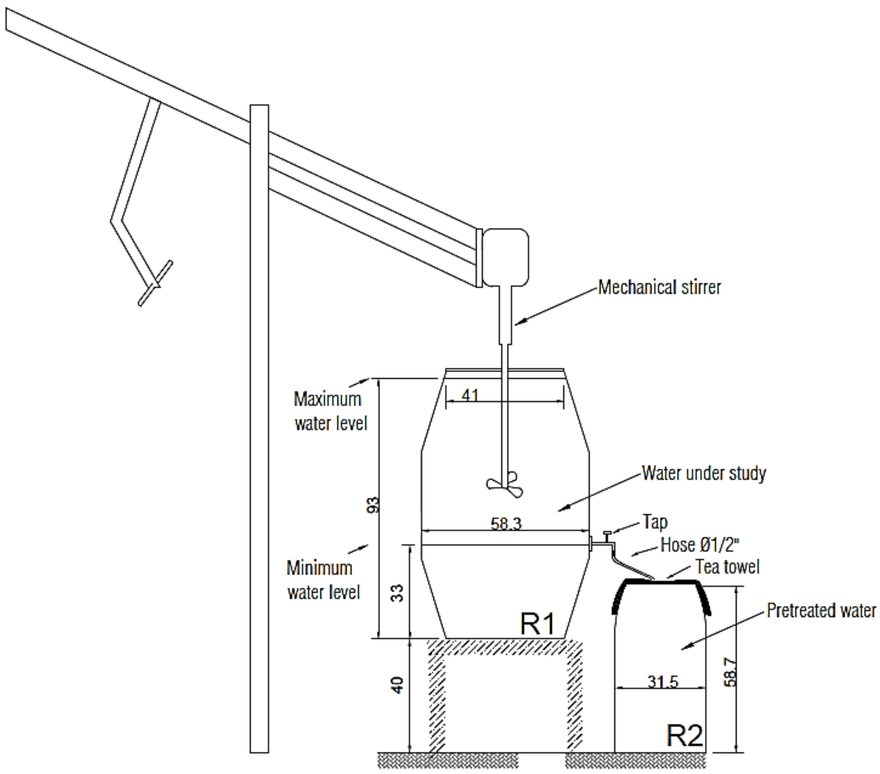

Figure 3. Tracer tests (NaCl = 100 mg.L^{-1}), in triplicate, to characterize the flow, (a) the continuous flow HSSF residence time distribution curve and (b) the concentration curve of the tracer as a function of void volume of the intermittent flow HSSF.

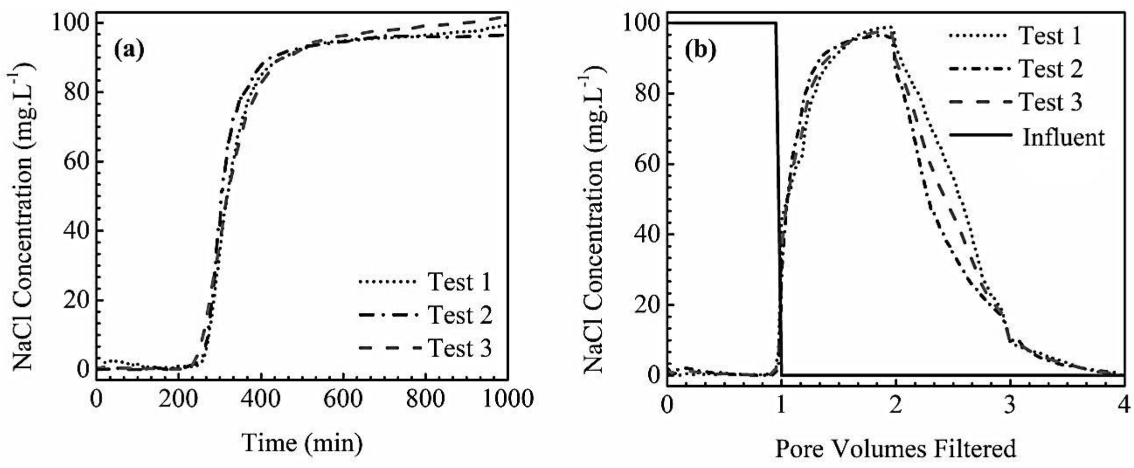

Figure 4. Performance of continuous and intermittent flow HSSFs in turbidity removal.

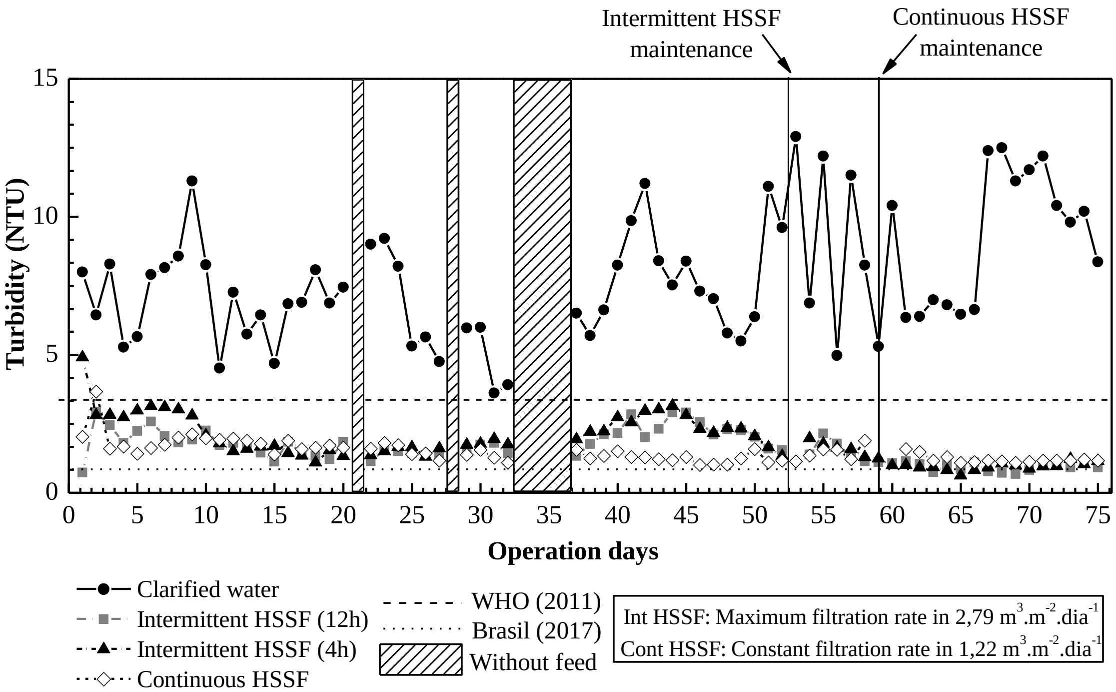

Figure 5. Performance of continuous and intermittent flow HSSFs in *E. coli* removal.

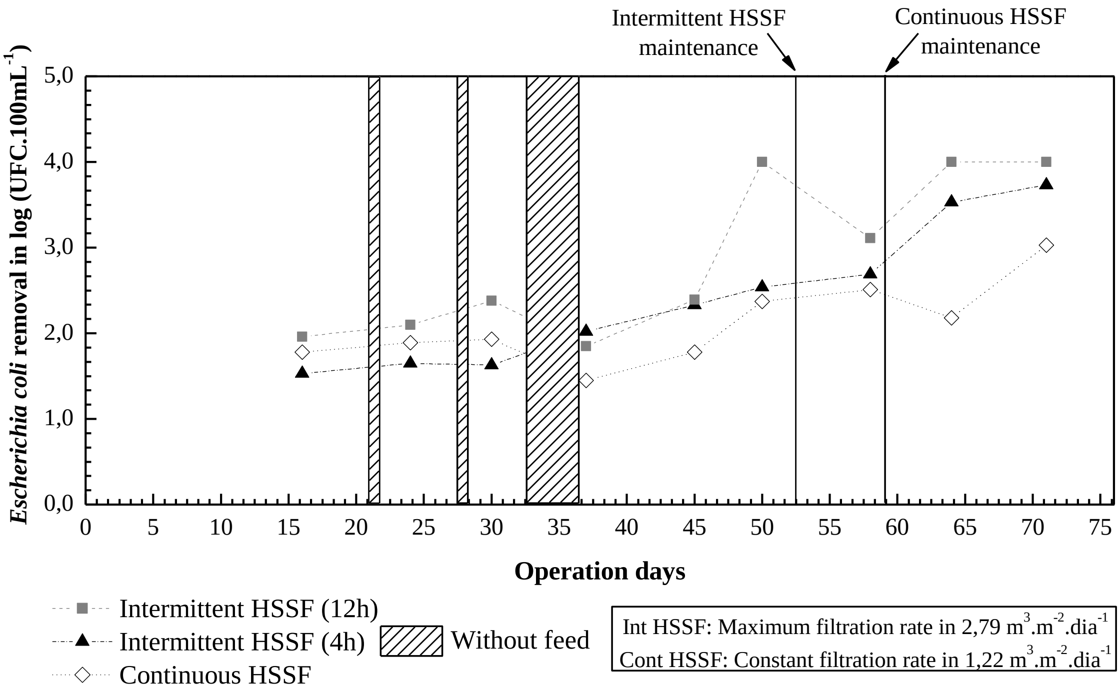

Figure 6. SEM photomicrographs of the blanket at 500x magnification, A) prior to filter operation, B) after continuous flow HSSF operation, C) after intermittent flow HSSF operation.

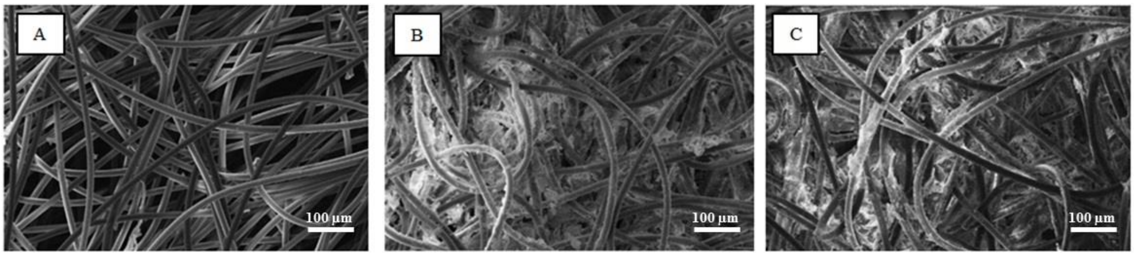

Table 1. Selection of filter media and support layer

Type of layer	Filter material	Type of commercial sieve	Aperture size (mm)	Discarded material size
Filter media	Fine sand	Corn meal	1.5 x 1.5	More than sieve opening
Support layer	Coarse sand	Rice	3 x 7	More than sieve opening
		Corn meal	1.5 x 1.5	Less than sieve opening
	Fine gravel	Coffee	5 x 12	More than sieve opening
		Beans	5 x 8	Less than sieve opening
	Coarse gravel	Chicken wire	11.5 x 11.5	More than sieve opening
		Coffee	5 x 12	Less than sieve opening

Table 2. Pretreatment performance with the natural coagulant (powder) extracted from *O. cochenillifera*.

Parameter	**Water under study**	**Clarified water**	**Variation**
	(mean ± standard deviation)		
Turbidity (NTU)	111 ± 17.3	7.83 ± 2.32	92.7 % ± 2.81
Apparent colour (HU)	134 ± 15.6	35.9 ± 5.03	73.9 % ± 4.48
True colour (HU)	25.9 ± 1.26	22.9 ± 1.00	11.7 % ± 3.96
pH	6.25 ± 0.07	6.90 ± 0.21	10.3 % ± 3.27
Total alkalinity ($mgCaCO_3.L^{-1}$)	25.82 ± 1.38	31.13 ± 2.07	20.9 % ± 9.80
Temperature (°C)	24.4 ± 2.41	24.0 ± 2.23	1.17 % ± 10.5
Zeta potential (mV)	-21.5 ± 8.14	- 22.5 ± 1.73	5.46 % ± 9.17
Total organic carbon ($mgC.L^{-1}$)	1.12 ± 0.50	1.66 ± 0.76	104.3 % ± 182
Escherichia coli ($CFU.100mL^{-1}$)	$3.2.10^3 \pm 1.5.10^3$	$3.3.10^3 \pm 1.7.10^3$	Without variation

SCSE/USP well water quality: turbidity = 0.70 NTU, true colour = 0 HU, pH = 6.18 and temperature = 23 °C.

Test conditions: *O. cochenillifera* dosage = 30 $mg.L^{-1}$, pH = 6.8, rapid mixing gradient = 250 s^{-1}, rapid mixing time = 60 s, slow mixing gradient = 83 s^{-1}, slow mixing time = 20 min and sedimentation velocity = 0.042 $cm.min^{-1}$.

Table 3. Performance of continuous flow and intermittent flow HSSFs in relation to physical-chemical parameters.

Parameter	**Intermittent flow** HSSF **(4 h of pause period)**	**Intermittent flow** HSSF **(12 h of pause period)**	**Continuous** HSSF
	(mean ± standard deviation)		
Apparent colour (HU)	19.0 ± 2.46	18.5 ± 2.85	19.1 ± 2.23
True colour (HU)	16.3 ± 1.96	15.3 ± 3.43	17.2 ± 3.33
pH	7.20 ± 0.14	7.06 ± 0.13	7.26 ± 0.10
Total Alkalinity ($mgCaCO_3.L^{-1}$)	30.22 ± 1.94	28.54 ± 1.83	28.61 ± 2.06
Temperature (°C)	24.3 ± 2.07	22.0 ± 1.86	23.9 ± 2.25
Total organic carbon ($mgC.L^{-1}$)	0.97 ± 0.38	0.84 ± 0.32	0.74 ± 0.35

Clarified water quality: apparent colour = 35.9 ± 5.03 HU, true colour = 22.9 ± 1.0 HU, pH = 6.90 ± 0.21, total alkalinity = 31.13 ± 2.07 $mgCaCO_3.L^{-1}$, temperature = 24.0 ± 2.23 °C and total organic carbon = 1.66 ± 0.76 $mgC.L^{-1}$.