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A Critical Overview of Household Slow Sand Filters for Water Treatment

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Abstract:

Household, or point-of-use (POU), water treatments are effective alternatives to provide safe drinking water in locations isolated from a water treatment and distribution network. The household slow sand filter (HSSF) is among the most effective and promising POU alternatives available today. Since the development of the patented biosand filter in the early 1990s, the HSSF has undergone a number of modifications and adaptations to improve its performance, making it easier to operate and increase users' acceptability. Consequently, several HSSF models are currently available, including those with alternative designs and constant operation, in addition to the patented ones. In this scenario, the present paper aims to provide a comprehensive overview from the earliest to the most recent publications on the HSSF design, operational parameters, removal mechanisms, efficiency, and field experiences. Based on a critical discussion, this paper will contribute to expanding the knowledge of HSSF in the peer-reviewed literature.

Keywords: water treatment; point-of-use; Biosand filter; *Schmutzdecke* layer; slow sand filtration

1. Introduction

The lack of water, sanitation, and hygiene (WaSH) is a worldwide concern that highlights social and economic disparities. In addition to evident barriers caused by poverty, one of the main obstacles of universal access to drinking water is the isolation of communities in low- and middle- income countries, whether by geographic distribution or by peripheral status. In these cases, Point-Of-Use (POU) technologies emerge as a solution as their promise is to enable people to improve the quality of drinking water at home through simple, safe, and low-cost treatment methods. A promising POU technology is the Household Slow Sand Filter (HSSF), a home scale of the slow sand filter, whose main widespread model is the patented biosand filter (BSF). Developed by Dr. David Manz in the early 1990s, the BSF presents specific construction instructions in which only the intermittent operation is recognized (i.e., on-demand operation) (CAWST, 2012). Meanwhile, HSSF also encompasses continuous operation (Maciel and Sabogal-Paz, 2020; Souza Freitas and Sabogal-Paz, 2019; Terin and Sabogal-Paz, 2019; Young-Rojanschi and Madramootoo, 2014) and different designs (Ahammed and Davra, 2011; Napotnik et al., 2020; Ngai et al., 2007; Sizirici et al., 2019; Yildiz, 2016).

As a slow sand filter, water purification by HSSF occurs through a combination of physicochemical and biological processes along and on the sand filter media. This combination promotes, in addition to the retention of impurities, the removal of organic/inorganic compounds and several pathogens responsible for diarrheal events (Jenkins et al., 2011; Mahlangu et al., 2012). Overall, many of the lessons, benefits, and limitations of HSSF were efforts from the conventional SSF literature (Huisman and Wood, 1974). Although these many findings were important for the HSSF development; there are still gaps in the HSSF literature that require specific studies due to different scales and flow regimes.

Given the lack of a paper summarizing the findings and experiences with HSSF, this manuscript aims to present a comprehensive and critical overview of HSSF design, operation parameters, removal mechanisms, efficiency, and field studies, among other key aspects of the filters presented in the literature. By elucidating the findings and scientific gaps of the HSSF literature, this paper allows for further development and optimization, as well as enabling proper deployment in vulnerable communities, based on efficient and affordable engineering to improve drinking water access.

2. Construction Materials and Design for HSSF

2.1. Filter Design

An HSSF comprises a structure filled with granular materials connected to an outlet tube (CAWST, 2012). Figure 1 shows a cross-section of the HSSF standard model and the water flow within the unit. The filtration layer is mainly responsible for the water treatment, while the separation and drainage layers serve as a support to prevent the filter media from moving down and blocking the outlet tube. Finally, the outlet tube conveys water from the lower layers (i.e., separation and drainage) to a storage reservoir.

In addition to the filter structure, other devices can assist the operation and the purification process, as shown in Figure 1. Placing a lid prevents contamination and proliferation of pests in the HSSF. The feed reservoir stores raw water and allows draining by gravity through the filter bed. The diffuser (e.g., perforated metal plate or a device with small holes) acts as an energy dissipation system to prevent biofilm disturbance and keep the filtration layer stable (Manz et al., 1993). A small hole at the top end of the outlet tube (i.e., no-siphon device) can reduce the effects of siphoning and possible emptying of the HSSF (Palmateer et al., 1999), while a valve at the end of the tube can control the maximum filtration rate (Devi et al., 2008).

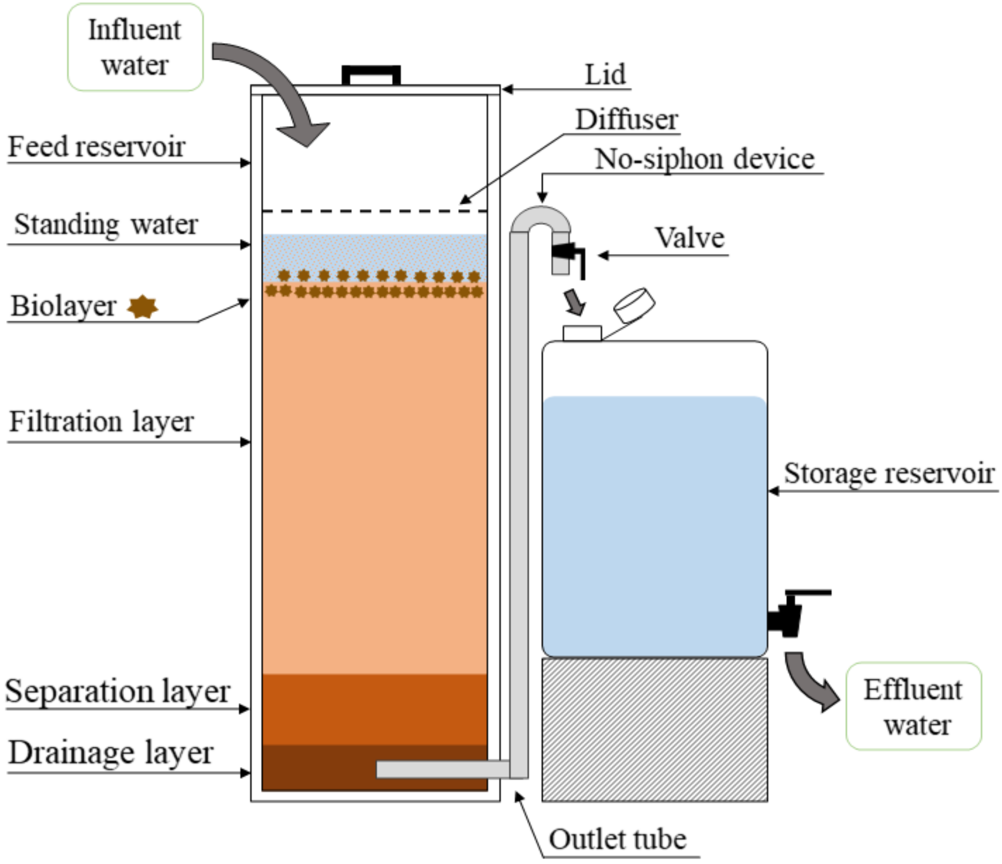

Figure 1 – Cross-section of the Household Slow Sand Filter standard model.

Other examples of HSSF design projects different from the standard model are illustrated in Figure S1 (Supplementary Material), including those with different sizes, structure materials, filter media depths, flow regimes, among others. Due to this variety of designs and operating conditions, full-scale HSSF can vary in height from 20 cm to more than one meter (Maciel and Sabogal-Paz, 2020; Napotnik et al., 2020).

2.2. Construction Materials for HSSF

A standard HSSF features a concrete structure with a plastic outlet tube. This model was widely spread, field-tested, and presents high user acceptability and evaporative cooling (Earwaker and Webster, 2009; Fabiszewski de Aceituno et al., 2012). However, concrete as an HSSF structure, in addition to its limiting portability, is susceptible to cracks and leaks when subjected to disturbances that can occur in a home (e.g., accidental collisions and impacts caused by transport) (Earwaker and Webster, 2009; Fiore et al., 2010). Therefore, studies began to evaluate the use of plastic in other HSSF components in addition to the outlet tube, as the body, lid, diffuser, and valves (Jenkins et al, 2011; Mahaffy et al., 2015; Napotnik et al., 2020). Despite being easier to acquire and handle, some of these novel designs have never been field-tested, whereas some of the old BSFs have shown high rates of sustained use in diverse field settings. Moreover, plastic may provide toxicity to drinking water (Higashi, 2016). This plastic toxicity has recently been solved by using Modified Polyvinylchloride (MPVC), a non-toxic plastic material used in drinking water distribution systems (Andreoli and Sabogal-Paz, 2020). However, despite being commercially distributed, MPVC pipe is more expensive than other plastics. Other construction materials have also been used in the filter structure, such as acrylic (Sabogal-Paz et al., 2020; Young-Rojanschi; Madramootoo, 2014) and galvanized iron (Smith, 2013). The former is a common structural material for laboratory studies used to better visualize the treatment within the HSSF.

These deficiencies underscore the need for caution while selecting the material and further studies for investigating ideal structures for HSSFs. Notwithstanding, the ideal material must consider socio-economic characteristics of target communities.

2.3. Filter Media

The filtration layer commonly comprises sand extracted from different sources, e.g., soil, quarry, and river (CAWST, 2012), while the separation and drainage layers are a combination of sized pebbles and gravels.

Filter media characteristics, such as effective size (d_{10}), uniformity coefficient (UC= d_{10}/d_{60}), percentage of fine particles (i.e., the percentage that passes through the # 150 sieve), density, and porosity, are important design parameters for the performance of HSSFs. Use of fine sand (d_{10} in the 0.15 mm range) as the filtration layer is recommended to increase the retention of suspended solids and microorganisms (Jenkins et al., 2011). Overall, the filtering material must have d_{10} between 0.15 and 0.20 mm, UC between 1.5 and 2.5, and a percentage of fines lower than 4% (CAWST, 2012). The drainage and separation layers should have grain sizes between 1 and 12 mm to provide support (CAWST, 2012).

Although there is consensus in the literature on the filter media characteristics; the filtration layer depth is still a variable that could be further researched. The Centre of Affordable Water and Sanitation Technology (CAWST) recommends 53.4 cm of filtration layer for a standard HSSF (CAWST, 2012), however, in the literature this value varies between 10 cm (Napotnik et al., 2020) and 80 cm (Ghebremichael et al., 2012). Several laboratory studies investigated HSSF with a media depth greater than 40 cm (Andreoli and Sabogal-Paz, 2020; Baig et al., 2011; Ghebremichael et al., 2012; Lynn et al., 2013; Murphy et al., 2010a; Nasser Fava et al., 2020; Young-Rojanschi and Madramootoo, 2015), while others evaluated reduced depths (i.e., ≤ 25 cm) to assess the feasibility of compact systems (Adeyemo et al., 2015; Freitas et al., 2021; Medeiros et al., 2020; Mwabi et al., 2012; Napotnik et al., 2017, 2020). However, despite being promising and efficient, the laboratory studies with novel HSSF designs must be field-tested to evaluate their sustained use.

Furthermore, to provide proper support and prevent the sand from washing into the outlet tube, the recommended thickness of the support layer can vary from 10 to 18 cm (Devi et al., 2008; Elliott et al, 2008).

3. Operational Parameters

3.1. Flow Regime

The HSSF was successfully implemented around the world adopting the intermittent flow regime (I-HSSF). In this operation, it is stated that the top sand layer should be kept wet the whole time (Manz et al., 1993). To reach this aim, the most acceptable design of an I-HSSF adopts an end of the outlet tube near 5 cm above the height of the sand layer (CAWST, 2012). The intermittent operation does not require an external supply unit and the area occupied in the residence is around 0.1 m^2 (Sabogal-Paz et al., 2020). The premise of this operation mode is that the filter works at its best capacity with an action of the biolayer during a pause period, which is a concept defined in Section 3.5.

With some modifications to the intermittent model, the HSSF can also be operated in a continuous flow regime (C-HSSF). The household would need one reservoir external to the HSSF and a control of the filtration rate, which can be performed both by direct pumping (Young-Rojanschi and Madramootoo, 2014) or by gravity feed (Maciel and Sabogal-Paz, 2020). Continuous operation requires bigger infrastructure; however, the user can benefit with a decrease in demand of effort to fill with water of the intermittent one. Figure S2 (Supplementary Material) illustrates differences between the I-HSSF and C-HSSF in terms of infrastructure and occupying area.

Although the continuous flow regime does not count on the pause period, its lower flow rate, compared to an intermittent regime (Section 3.2), allows the unit to reach good efficiencies in turbidity and microorganism reductions. When comparing C-HSSF and I-HSSF treating the same daily volume, the authors have found a better performance of the continuous ones. Andreoli and Sabogal-Paz (2020) found 4.3 log and 2.7 log of *E. coli* reduction in continuous and intermittent operation, respectively. Similarly, Young-Rojanschi and Madramootoo (2014) observed 3.7 log and 2.1 log of *E. coli* reduction in C-HSSF and I-HSSF, respectively.

Nevertheless, some authors argue that users of I-HSSF can consider a low filtration rate as an obstacle for the filter acceptance (CAWST, 2012; Earwaker and Webster, 2009; Ghebremichael et al., 2012). The low filtration rate is inherent to the continuous operation.

3.2. Filtration Rate

The filtration rate, or hydraulic loading rate, is defined as the flow rate divided by the surface area of a filter. This operational parameter is expressed in units of length over time. In the HSSF literature, the filtration rate is more commonly expressed in terms of m h^{-1}, given that the filtration cycle takes hours, rather than days as seen for SSFs.

The I-HSSF presents relatively high filtration rates, compared to other household water treatment methods, achieving its maximum just after the introduction of a charge and declining to zero between filter feedings (Kubare and Haarhoff, 2010; Ngai, 2014; Napotnik et al., 2017). The high filtration rate in the filter cycle of I-HSSF lasts just a few minutes. Terin *et al.* (2021) demonstrated the lowering of the filtration rate after 40 and 20 minutes in I-HSSF models with and without the maximum level of water control, respectively, following asymptotic decay of the flow. The Biosand filter construction manual states a maximum filtration rate of 0.40 m h^{-1} (CAWST, 2012), while filtration rates up to near 1.50 m h^{-1} are also applied (Baig et al., 2011).

The researchers who have studied C-HSSF presented a filtration rate ranging from 0.010 m h^{-1} (Young-Rojanschi and Madramootoo, 2014) to 0.063 m h^{-1} (Medeiros et al., 2020). In this operation mode, a higher filtration rate favours the higher daily production of treated water, while the lower filtration rate favours the higher quality of the treated water. However, it should be noted that the drawback of the lower filtration rate is related to the user's immediate demand for water (filling a cup), rather than the daily volume production.

3.3. Maintenance

The cleaning (or maintenance) of the HSSF filter media must be done as clogging results in insufficient water production, that is, when the filtration rate is so low that during a day the filter is unable to produce enough water for household consumption (Elliott et al., 2008). The cleaning methods most often used were superficial agitation (< 1 cm) and 5 cm stirring (Table S1 - supplementary material). Some studies also carried out maintenance by removing 5 cm of the filtration media

(Singer et al., 2017) and by the wet harrowing method (Jenkins et al., 2011; McKenzie et al., 2013; Tiwari et al., 2009).

Singer et al. (2017) compared three cleaning methods for I-HSSF media: surface agitation (< 1 cm), 5 cm stirring, and 5 cm replacement. The cleaning methods recovered 76, 82, and 138% of the initial filtration rate, respectively. Despite the significant improvement of the third method, procedures of draining, scraping, and restarting the system can take several days, even for a small system (i.e., bench scale), and the ability to remove bacteria can be reduced by causing extensive disturbance to the biological layer (Barrett et al., 1991). The average time for recovery of post-maintenance filters can vary depending on the operational mode and the maintenance method (Duke and Mazumber, 2009; Kennedy et al., 2013; Nair et al., 2014; Singer et al., 2017). According to Singer et al. (2017), recovery times after cleaning vary from 8.5 to 23 days using the methods of surface agitation and 5 cm replacement, respectively. Furthermore, frequent maintenance activities can affect the biological layer stability and the HSSF overall efficiency. For instance, Maciel and Sabogal-Paz (2020) reported that an intermittent HSSF was unable to achieve an *E. coli* removal rate greater than 1 log due to frequent maintenance.

Recently mentioned in the literature, one of the optimizations for improving HSSF maintenance is using materials at the filter media top, such as non-woven blankets. These materials retain some particles and consequently prevent impurities from passing directly to the filter media, prolonging the filter run, and improving the HSSF performance. It is also easily removed, washed, and replaced in the unit (Maciel and Sabogal, 2020; Souza Freitas and Sabogal-Paz, 2019; Terin and Sabogal-Paz, 2019).

3.4. Feeding Volume

The volume that fills the I-HSSF inlet reservoir in each batch is so-called feeding volume, or charge volume. The I-HSSF is generally designed with reservoir dimensions corresponding to the maximum volume that can be poured into the filter at one time. The concrete-made CAWST (CAWST, 2012) filter admits 12 litres feeding volume, while there is a plastic version designed to receive 20 L, as the Hydraid from The Dow Chemical Company (Triple-Quest, 2010).

Results obtained in laboratories pointed out that better efficiencies in microorganism reductions were achieved when the feed volume was equal or less than the filter media and support layer pore volume (Baumgartner et al., 2007; Elliott et al., 2008; Nair et al., 2014). The operational parameter pause period, defined in the next section (3.5), has implications for the selection of feeding volume, frequency of feeding, and duration of filtration cycles (Elliott et al., 2008).

Additionally, the feeding volume is also related to the hydrostatic head, the height of water after filling the I-HSSF reservoir. A reduced nominal head results in a lower filtration rate and lower biofilm shear forces at the beginning of batch filtration, improving the efficiency of the water treatment (Jenkins et al., 2011). For that reason, the maximum elevation head is a filter design parameter considered when defining the feeding volume (Elliott et al., 2015). Nevertheless, although the reduction in feeding volume generates better quality water, it should be pondered if it is worth the loss of daily water production. Moreover, any design changes for improved performance must be weighed up against acceptability and their potential effects on consistent, exclusive use.

3.5. Pause Period

The I-HSSF cycle has steps as the fill of the influent reservoir, the flow of the water through the filter, and a resting time before the next feed. The time after the water stops flow and before a new water addition is called the pause period, or idle time. The *Biosand filter construction manual* states that the pause period should be a minimum of 1 hour and no longer than 48 hours (CAWST, 2012).

Since the filtration rate declines with the filter retaining impurities, it is not possible to predict when the water will stop flowing through the filter media. Due to this, daily measuring of the pause period is not practical. On the contrary, it is easier to monitor the total retention time, which includes the pause period time plus the filtration time (Ngai and Baker, 2014). In line with this, the scheduled times in which the I-HSSF will be fed should be equal or higher than the total retention time.

The pause period has been appointed as essential for the I-HSSF treatment. Biological and physicochemical processes inside the sand column need appropriate time to clear pore spaces and biofilm adsorption sites filled with contaminants (Jenkins et al., 2011). This operational parameter is trusted to hold an efficient water treatment process in such a way that higher filtration velocities can be used in I-HSSF compared with SSF (Kubare and Haarhoff, 2010). The mechanisms that act in the pause period are (i) the predation of pathogens at the top of the filter in the biolayer, (ii) predation below the biolayer, (iii) natural die-off of microorganisms in the bed in the absence of sufficient oxygen and nutrients and (iv) adsorption in the filter media (Ghebremichael et al., 2012; Kennedy et al., 2013; Singer et al., 2017).

Summarizing the HSSF process parameters, Table S2 (supplementary material) presents the maximum filtration rates, feeding volumes, and pause periods reported in the literature, for both I-HSSF and C-HSSF.

4. Mechanism of HSSF

4.1. Biological Processes

Biological processes occur along and on the HSSF media bed. With the water flow, microorganisms and organic matter are adsorbed favoring the development of biofilm around the sand granules (Elliot et al., 2011; Wang et al., 2014). However, the main removals have been demonstrated to take place within the *schmutzdecke* due to the high pathogen adsorption rate on this biological layer (Young-Rojanschi and Madramootoo, 2014).

Schmutzdecke (the German word for dirty layer) is a biological layer or biofilm on the first 5 cm of the sand-water interface within a slow sand filter (Unger and Collins, 2008; Young-Rojanschi and Madramootoo, 2014). This biolayer originates from the adsorption of organic matter, especially microorganisms, attached to a solid surface (i.e., sand) and imbued in a matrix of mineral precipitates and extracellular polymeric substances (EPS) (Huisman and Wood, 1974; Ranjam and Prem, 2018). Its development goes through a cyclical process, starting with the bacteria producing an extracellular gelatinous matrix for protection, which also increases microorganisms' attachment (Law et al., 2001), followed by the formation of microcolonies and the increase of cell-cell communication, and ending with the detachment and dispersion of some cells into the environment, potentially starting a new cycle (Sauer et al., 2002).

In HSSF, as well as SSF, the HRT is the key factor for *schmutzdecke*'s initial establishment and maintenance, because it allows particles suspended in water to settle and come into contact with the filter media top (Huisman and Wood, 1974), and is integrated into it by mass attraction or electrical forces (Balen, 2018). The biolayer formation in HSSF is expected to happen within 40 days (CAWST, 2012). However, this time may vary depending on the temperature, source water, nutrient levels, and colonizing microorganisms (Elliot et al., 2008; Napotnik et al., 2017).

EPS is the major component of the biofilm matrices and is responsible for its cohesion and stability (Decho, 2000). Other properties of EPS include aggregation of bacterial cells, water retention, binding of enzymes, and enzymatic activity. All these features combined generate a microenvironment favourable to the biological development that allows microorganisms to survive (Flemming et al., 2016).

Bacteria are generally the predominant microorganism in the HSSF *schmutzdecke* (Pompei et al., 2017; Wang et al., 2014) due to their low sizes, high growth rates, adaptation capacity, and extracellular polymer production (Characklis and Marshall, 1990). However, algae, fungi, helminths, microcrustacean, protozoa, rotifers, and several insect larvae may also be present (Andreoli and Sabogal-Paz, 2020; Medeiros et al., 2020; Terin and Sabogal-Paz, 2020). This biodiversity tends to come into balance with the time of operation, creating a self-regulating food chain that is essential to the efficiency of the *schmutzdecke* (Nakamoto et al., 2014).

Although bacterial activity is most prominent in the upper filter layer, it remains along the filter bed, gradually decreasing as the supply of oxygen and food becomes scarce (Ranjan and Prem, 2018). This deeper zone is, therefore, a continuation of the *schmutzdecke* with considerable microbial diversity and expressive concentrations of carbohydrates and protein (Unger and Collins, 2008).

Water purification can be attributed to biological processes occurring simultaneously within the *schmutzdecke* and along the filter bed, such as natural die-off, predation, excretion of toxins, and competition for food (Huisman and Wood, 1974). While some macroinvertebrates can prey on algae and diatoms (Haarhoff and Cleasby, 1991), some algae and protozoa actively contribute to the reduction of suspended and attached bacteria (Guchi, 2015; Ribalet et al., 2008; Siqueira-Castro et al., 2016; Wichard et al. 2005) and (oo)cysts of *Cryptosporidium parvum* and *Giardia duodenalis* (Siqueira-Castro et al., 2016). Some genera of algae may also contribute to the reduction of bacteria including coliforms by producing and excreting polyunsaturated aldehydes - a toxin with an antibacterial effect (Ribalet et al., 2008; Wichard et al. 2005). Moreover, the bacterial population acquires energy for replication and metabolic functions through the oxidation of organic matter suspended in water, including dead pathogens (Guchi, 2015). However, the demand for food is greater than the supply, forcing microorganisms to compete for food (Huisman and Wood, 1974; Ranjam and Prem, 2018).

Biological processes directly impact filter efficiency, promoting an inhospitable environment that, in addition to hindering the multiplication or reproduction of many pathogens, is also responsible for their deaths and/or inactivation (Ranjam and Prem, 2018). Studies reported that when these processes are combined with the physicochemical mechanisms inherent to the HSSF, removal rates can increase between 3 and 5 logs for bacteria, protozoa, and viruses (Adeyemo et al., 2015; Freitas et al., 2021; Terin et al., 2021; Wang et al., 2014).

Additionally, sorption in the biofilms is not compound-specific (Flemming et al., 2016); therefore, in addition to microorganisms, other contaminants can also be trapped, including nutrients, nitrogen, phosphorus, iron, aluminium, potassium, chloride, enzymes, and toxins (Sabogal-Paz et al., 2020), considerably improving the water quality.

4.2. Physicochemical Filtration

While the filter is not fully mature, physicochemical filtration mechanisms are prominent regarding particle removal and improving water quality (Weber-Shirk, 2002). Some of these mechanisms are straining, sedimentation, inertial and centrifugal forces, diffusion, and electrostatic attraction (Huisman and Wood, 1974).

The presence of bivalent ions (Ca^{2+}; Mg^{2+}) in water may favour the complexation process (Wang et al., 2014), whereas the presence of aluminum may coat the filter media surfaces increasing particle attachment or it may cause some reduction of the pores by the deposition of hydrous aluminum complex (Weber-Shirk and Chan, 2007) and, similar to iron, it may benefit precipitation, increasing the settling velocity of the suspended particles (Huisman and Wood, 1974). Adsorption is a result of mainly electrical forces, chemical attraction which are related to the colloidal size, solution ionic strength, sand surface area and physicochemical nature of the particles in the filters (Huisman and Wood, 1974; Treumann et al., 2014; Weber-Shirk and Dick, 1997a). The attachment efficiency depends on suspended particles, porous media, solution chemistry, and filter medium length (Tufenkji and Elimelech, 2004). Sand composition could be modified by the presence of elements such as iron and aluminium, for instance, favouring electrostatic attraction and adsorption capacity (Ahammed and Davra, 2011; Bradley et al., 2011; Hijnen et al., 2004; Napotnik et al., 2020). Detachment occurs when hydrodynamic forces are greater than adhesive forces. It can be affected by the chemical (pH, temperature, ionic strength) and physical (flow rate, hydraulic retention time) properties of the liquid (Song et al., 2020; Weber-Shirk and Chan, 2007). From these mechanisms, in general, turbidity, bacteria, virus, and protozoa are reduced within the HSSF.

Filter maturation may happen because of physicochemical processes, with clogging of filter media due to particle settling (Napotnik et al., 2017) removing turbidity. Particle concentration decreases with the increase in particle size and larger particles (around 50 µm) are removed more superficially by straining (Napotnik et al., 2017; Song et al., 2020). Colloids smaller than the void size are removed by attractive forces (Song et al., 2020). Previously removed particles may improve the straining mechanism even further through interparticle attraction (Weber-Shirk and Dick, 1997a).

For the removal of microorganisms, bacteria (e.g., *E. coli*) are predominantly removed by adsorption, interception, straining and diffusion (Napotnik et al., 2020; Schijven et al., 2003; Weber-Shirk and Chan, 2007), while two of the most important physicochemical mechanisms for removing virus are adsorption and molecular diffusion (Napotnik et al., 2020; Schijven et al., 2003), and finally, regarding protozoa, *Cryptosporidium* oocyst and *Giardia* cyst removals are ruled by straining, mainly when the media consists of irregular sand grains and, physicochemical filtration (Hsu et al., 2001; Schijven et al., 2003; Tufenkji et al., 2004). Additionally, microorganisms can attach to particles in water forming an aggregate easier to be removed by filtration (Bradley et al., 2011; Wang et al., 2014).

Individual and synergistic contributions of physical, operational, and biological characteristics still need further research (Wang et al., 2014). Understanding these mechanisms may give insight into filters' potential, regarding physical, chemical, and microbiological treatment of raw water (Weber-Shirk and Chan, 2007).

5. Effect of HSSF Treatment on Physicochemical Water Quality

As previously described, the biological and physicochemical mechanisms in filters play a crucial role in HSSF performance. Moreover, different filters' design, operational modes (i.e., pause period, ripening, and hydraulic rate), maintenance, and water source quality strongly influence the filter efficiency. Since filter operation has multifactor conditions, there are wide values for the average removal of physicochemical water quality parameters. Furthermore, these average values may differ under other experimental conditions. For instance, removal values range from 0 to 98% for turbidity, 2% to 91% for organic matter, <50% to >90% for metals, <5% to 53% for nitrogen compounds and ≤20% to 99% for emerging pollutants. Table S3 (supplementary material) presents these removal values reported in the HSSF literature.

5.1. Turbidity

Several studies have evaluated the ability of HSSFs to remove turbidity. In general, filters present average removal efficiencies of 75% or greater, often reaching removals above 90% (Jenkins et al., 2011; Murphy et al., 2010a; Singer et al., 2017; Young-Rojanschi and Madramootoo, 2014). However, some studies have reported low removal (i.e., ≤ 50%), mainly in conditions with low turbidity in influent water (e.g., preserved groundwater and pre-treated water) (Adeyemo et al., 2015; Andreoli and Sabogal-Paz, 2020; Medeiros et al., 2020; Young-Rojanschi and Madramootoo, 2015). HSSFs can produce water with turbidity within the limit recommended by WHO for home water treatment, of 5 NTU (WHO, 2017), and, frequently, below 1 NTU (Andreoli and Sabogal-Paz, 2020; CAWST, 2012; Elliott et al., 2008; Jenkins et al., 2011; Kennedy et al., 2013; Napotnik et al., 2017; Souza Freitas and Sabogal-Paz, 2020; Young-Rojanschi and Madramootoo, 2014).

The declining flow due to ripening improves the efficiency of HSSF in removing turbidity (Ahammed and Davra, 2011; Elliott et al., 2008; Nair et al., 2014). In this context, *schmutzdecke* development can increase the turbidity removal, without direct relation to the influent water turbidity (Adeyemo et al., 2015). Operational mode also affects the turbidity removal because of differences in feeding strategies and output flows. The constant and low filtration rate of C-HSSF promotes higher turbidity removal than the higher and declining rate of I-HSSF. In bench-scale HSSFs, Young-Rojanschi and Madramootoo (2014) observed 96% and 87% turbidity removal by continuous and intermittent filters, respectively. As it is more efficient, C-HSSF is less dependent on the influent water quality than I-HSSF (Maciel and Sabogal-Paz, 2018), however, its biological layer developed is more sensitive to interruptions in the feeding (Souza Freitas and Sabogal-Paz, 2020).

Napotnik et al. (2017) observed that deeper filter beds (54 cm) do not necessarily appear to improve turbidity removal in I-HSSF as long as the feed volume corresponds to the void volume of the unit. On the other hand, in cases of higher feed volumes, deeper beds may enhance particle retention. Another operational parameter that affects the I-HSSF efficiency is the pause period. Pause period may provide sedimentation and reduce turbidity (Freitas and Sabogal-Paz, 2019; Young-Rojanschi and Madramootoo, 2015). Jenkins et al. (2011) achieved up to 5.9% greater turbidity removals by increasing the pause period from 5h to 16h. Removal improvements were also observed in longer residence times (> 24 h) (Young-Rojanschi and Madramootoo, 2015).

Although necessary for the proper functioning, the maintenance activity removes the clogged particles at the bed top, increasing the intergranular voids, which consequently decreases the head loss, the particles settling, and the HSSF's ability to remove turbidity. Singer et al (2017) observed reductions of up to 4.6% in the removal of turbidity after cleaning processes. In addition, the time after maintenance was reported as one of the operational variables most correlated with the turbidity removal (Jenkins et al., 2011; Maciel and Sabogal-Paz, 2020).

5.2. Organic Matter

Organic matter removal can be indirectly evaluated by total organic carbon (TOC), colour, among other water quality parameters. HSSFs are not as efficient for removing organic matter (Table S3) due to its low capacity to remove dissolved compounds, such as humic substances, which are capable of attributing colour and taste to water (CAWST, 2012).

The reported TOC displays average removals between 2% and 30% (Bradley et al, 2011; Freitas et al, 2021; Mahlangu et al., 2012; Lynn et al., 2013; Ghebremichael et al., 2016; Andreoli and Sabogal-Paz, 2020, Terin et al, 2021). The best results were sometimes associated with lower filtration rates, probably because of organic matter sedimentation. Despite this limitation, modified HSSFs can achieve high TOC removals (up to 91%), for instance, the version operated with a hybrid approach (Sizirici et al., 2019) and the alternative enriched with an iron oxide layer (Maeng et al., 2015) – a well-known coagulant, which contributes to the removal of dissolved organic matter through aggregation and flocculation.

As mentioned, colour can be used as a surrogate for OM. Colour removal rates vary between 5% and 25% (Medeiros et al., 2020; Souza Freitas and Sabogal-Paz, 2019). Higher removal rates were reported (95-97%) when associated with removal of cyanobacteria, which were the main source of colour in the influent water evaluated by Terin and Sabogal-Paz (2019).

5.3. Metals

CAWST defines HSSF as inefficient removing iron and dissolved chemical compounds (CAWST, 2011); however, some studies observed considerable removal of metals and often simple modifications to the BSF model provided promising results.

The reported metal removals depended on the filter design parameters, but mostly on water chemistry.

Palmateer et al., (1999) reported 75% toxicity reduction after the filtration of water containing mercury, based on *Microtox* essay, and an $HgCl_2$ removal of more than 92%. The authors stated that mercury removal was partially impaired by a break in the schmutzdecke due to turbulence caused by a leakage around the diffuser, hence, HSSF efficiency could be even higher (Palmateer et al., 1999).

Arsenic removal by HSSF was more extensively studied than any other metal (Table S3) due to its worldwide presence in groundwater. Nevertheless, removal rates vary considerably, ranging from 39% (Chiew et al., 2009) to 95% (Avilés et al., 2013). Modifications such as adding a layer of crushed bricks, adding nails to the sand or to the diffuser and using oxidized commercial fibre showed to considerably increase HSSF efficiency removing arsenic by providing the filtration with additional mechanisms of adsorption and/or co-precipitation (Avilés et al., 2013; Devi et al., 2008; Ngai et al., 2007; Smith et al., 2017). Furthermore, water composition plays an important role in arsenic removal by household filtration (Berg et al., 2006; Chiew et al., 2009). For example, while the oxidation of the iron in water may improve arsenic removal in filters, phosphate may compete for adsorption sites, hindering arsenic removal (Chiew et al., 2009).

Regarding iron removal, mean rates ranged from 73% (Mahlangu et al., 2012) to > 93% (Ngai et al., 2007) were reported. Phosphate removals can vary between 39% (Mwabi et al., 2011) and 90% (Berg et al., 2006). Although 99.9% removal of fluoride was reported for a HSSF treating synthetic water (Mwabi et al., 2011), poor removal rates (0% - 26%) were observed for natural waters (groundwater and surface water) (Mahlangu et al., 2012; Mwabi et al., 2011). Similar behaviour was observed for calcium removal (Mwabi et al., 2011). Magnesium removal rates were reported to be around 50% (Mwabi et al., 2011); Mahlangu et al., 2012). As seen in arsenic removal, amendments to the BSF CAWST model have the potential to increase the removal of some of the considered metals (Mahlangu et al., 2011; Ngai et al., 2007). Furthermore, HSSF showed to be able to reduce the aforementioned metal concentrations to acceptable levels.

It is noteworthy, however, that the presence of inorganic compounds in water could be increased after filtration by HSSF if the influent water has low concentrations of such contaminants. Sabogal-Paz et al. (2020) reported an increase in the concentration of chloride, sulphate, silica, aluminium, calcium, iron, potassium, magnesium, and sodium after the filtration of simulated rainwater by bench-scale HSSF. According to the authors, these results can be attributed to filter media leaching, as previously reported by Young-Rojanschi and Madramootoo (2015) (Sabogal-Paz et al., 2020).

5.4. Nitrogen Compounds

Nitrate removal rates in HSSF vary between < 5% to 53% (Mwabi et al., 2011; Kennedy et al., 2012; Mahlangu et al., 2012; Avilés et al., 2013; Romero et al., 2020). However, some studies have also shown an increase in the concentration of nitrate and nitrite in HSSF effluent, especially when influent waters presented high nitrogen content (Chiew et al., 2009; Pompei et al., 2017; Sabogal-Paz et al., 2020). According to Murphy et al (2010), the high nitrate and nitrite concentration in the effluent is a result of a dynamic nitrogen cycling (i.e., nitrification and denitrification) that can occur within the filter media.

Complete denitrification was achieved only by Snyder et al. (2016) in a vinegar-amended anaerobic biosand filter. Although not common in HSSF, anoxic and anaerobic metabolisms could be an option for improving the nitrogen removal in HSSF, but they can be controlled by the amount of organic carbon. Despite this, researchers should be careful about the concentrations of nitrite and nitrate in treated water, which is an undesirable result given the consequences of their ingestion for human health. The formation of anoxic zones is most common in I-HSSF with long pause periods (Young-Rojanschi and Madramootoo, 2014).

5.5. Emerging Pollutants

There is little information on emerging contaminants removal by HSSF. While no significant and oscillating removal rates (0.00 - 93.3%) were reported for the pesticide metaldehyde (Outhwaite and Campos, 2010), the retention of the herbicide metolachlor exceed 99% (Palmateer et al., 1999). However, both studies had aspects that need to be considered. Outhwaite and Campos (2010) presented a short-duration study. Considering that the *schmutzdecke* was already mature at the beginning of the tests, it is reasonable to expect that the microbiological community would pass through an adaptation period before being able to metabolize the pesticide; therefore, longer studies are needed. On the other hand, Palmateer et al. (1999) based metolachlor removal on the cumulative retention, which should not be compared to mean removal rates.

Recently, it has been shown that HSSF is efficient for removing pharmaceuticals and personal care products (PPCP) (e.g., paracetamol, diclofenac, naproxen, ibuprofen, methylparaben and benzophenone-3) and resilient to its effects, individually and as a mixture (Pompei et al., 2017; Pompei et al., 2019). However, there is preliminary evidence that the PPCPs may affect the schmutzdecke development and microbial community, possibly affecting the HSSF's efficiency in the long term (Pompei et al., 2017).

Poor removals were reported for endocrine disruptors bisphenol-A and estrogen. Sabogal-Paz et al. (2020) reported 3 ± 8% of removal of bisphenol-A from rainwater by a bench-scale I-HSSF. While Kennedy et al. (2013) observed between 11.4 and 15.6% removal of estrone, estriol and 17α- ethinyl estradiol, using full-scale I-HSSF fed with spiked lake water, results which were compatible to SSF, according to the authors. Both studies propose using a post-filtration step to improve contaminant removal (activated carbon and chlorination, respectively). Sabogal-Paz et al. (2020) suggested using activated carbon to remove DOC and bisphenol-A, while Kennnedy et al. (2013) showed that oxidation by chlorine can result in more than 98% removal of estrogens.

6. Effect of HSSF Treatment on Microbiological Water Quality

A summary of several studies of microbiological reduction by HSSF is presented in Table S4 (supplementary material). Since filter operation has multifactorial conditions, as well as for the physicochemical water quality parameters, there are wide values for the average removal of microbiological parameters.

6.1. Bacteria

Bacteria removal by HSSF is widely reported and most studies show an average reduction between the 1.00 and 2.00 log; nevertheless, a wide efficiency range was noticed due to the diverse experimental parameters (Table S4).

Different sand sizes used in HSSF showed diverse bacterial removal performance. Most studies used effective sand size (d_{10}) smaller than 0.24 mm, showing an average reduction over time from 1.17 to 3.90 log (Andreoli and Sabogal-Paz, 2020; Elliott et al., 2008; Maciel and Sabogal-Paz, 2020; Jenkins et al., 2011; Lynn et al., 2013; Napotnik et al., 2017, 2020; Nasser Fava et al., 2020; Singer et al., 2017; Souza Freitas and Sabogal-Paz, 2020; Terin et al., 2021; Young-Rojanschi and Madramootoo, 2014). HSSF with greater sand sizes (between 0.30 and 0.90 mm) seems to have lower bacteria removal rates (0.33 to 2.60 log) (Ghebremichael et al., 2012; Sizirici et al., 2019; Yildiz, 2016).

Modifications on filter media composition have been tested to improve HSSF efficiency. Ahammed and Drava (2011) used 10 cm of iron coated sand in the filter media and reached an average *E. coli* reduction of 3.10 log, an improvement of almost 1.00 log compared with a standard biosand filter. The presence of iron oxides could neutralize the negative charge of bacteria, enhancing the adsorption on sand grains (Ahammed and Davra, 2011; Napotnik et al., 2020). However, other modifications in filter media did not positively impact the removal of bacteria (Baig et al., 2011; Devi et al., 2008; Elliot et al., 2015; Ghebremichael et al., 2012; Mwabi et al., 2012; 2013; Sizirici et al., 2019; Yildiz, 2016).

Analysing the depth profile in the HSSF sand bed, some authors have reported that most of the bacterial removal occurs within the top 5-10 cm layer. Nair et al. (2014) showed that approximately 1.00 log of total coliform reduction occurs in the first 10 cm. Another study demonstrated that *E. coli* removal in the top 10 cm was significantly higher in an I-HSSF, when compared to deeper layers, reaching more than 2.00 and 1.50 log in a C-HSSF and I-HSSF, respectively (Young-Rojanschi and Madramootoo, 2014). Results reported by Freitas et al. (2021) also suggested a higher removal in the first 5 cm layer. These results highlight the importance of the *schmutzdecke* on HSSF performance.

Several studies reported that HSSF efficiency is improved after the ripening period, with an average bacterial reduction of ≤ 1.00 log before ripening and a significant increase in the following days (Arnold et al., 2016; Baig et al., 2011; Kennedy et al., 2013b; Maciel and Sabogal-Paz, 2020; Nair et al., 2014).

Despite the importance of the *schmutzdecke* in HSSF, maintenance is eventually necessary and, by removing most of the biofilm layer, it has an adverse impact on the bacterial removal efficiency. Singer et al. (2017) reported a decrease in efficiency by 0.16 – 0.83 log, varying with the maintenance method used. Freitas and Sabogal-Paz (2019) and Kennedy et al. (2013) also demonstrated lower removal rates after cleaning and 15-17 days to recover. Furthermore, Maciel and Sabogal-Paz (2020) presented a positive correlation, showing higher *E. coli* reduction with a greater time after maintenance.

Schmutzdecke development and particle straining lead to head loss and a reduced HSSF filtration rate, which may also influence bacterial removal. Kennedy et al. (2012) demonstrated that the decrease in the flow rate from 0.74 L min^{-1} to 0.42 L min^{-1} resulted in an increased faecal coliform removal. Jenkins et al. (2011) also reported that decreasing the flow rate by reducing the nominal head above the static water level from 30 cm to 20 or 10 cm, improves the bacterial removal by 0.10 – 0.16 log.

Some studies demonstrated that longer residence time resulted in higher bacterial removal by predation and natural die-off (Baumgartner et al., 2007; Elliott et al., 2006, 2008; Souza Freitas and Sabogal-Paz, 2020). Ghebremichael, et al. (2012) indicated that 20 and 22 h of idle time increased *E. coli* reduction by 2.00 log, compared to 1.5 h. Jenkins et al. (2011) showed that longer resting periods (15 h) enhance the bacterial removal by 0.29 log, compared with shorter idle time (5 h). However, too long pause periods (> 24 h), did not improve the bacterial removal any further

(Ghebremichael, et al., 2012, Napotnik et al., 2020; Young-Rojanschi and Madramootoo, 2015). Furthermore, using feed charges with more than 50% of the filter pore volume generated lower bacterial removal caused by shorter residence time (Elliott et al., 2008; Nair et al., 2014).

The operation regime may also have an impact on removing bacteria. Kereita et al., (2008) showed that C-HSSF was able to reduce more than 2.00 log. Another study with traditional and compact HSSF (i.e., 50 and 25 cm of filtration layer) in continuous flow showed an average of 2.00 log and maximum of 3.62 log reduction (Freitas et al., 2021). Maciel and Sabogal-Paz (2020) and Young-Rojanschi and Madramootoo (2014) reported superior efficiency by continuous filters compared to intermittent, with average removal higher than 2.00 log.

Non-microbiological influent water characteristics may also affect HSSF efficiency. Biosand filters had superior performance removing bacteria when the water presented high turbidity (Mwabi et al., 2012; 2013). Moreover, it is inferred that each additional NTU in influent water may increase the bacterial removal by 0.0035 log (Jenkins et al., 2011). This could be explained by the fact that bacteria are more likely to be attached to larger particles when in water sources with high turbidity, which will be easily retained within HSSF.

Temperature can alter the HSSF performance, however, studies reporting it are limited. Arnold et al. (2016) placed filters in rooms with controlled temperatures (4, 12, 18 and 27 ºC) after the ripening period. Filters placed at lower temperatures had an efficiency decrease, but after 25 days all filters showed similar efficiency. Another work observed that lowering influent water temperature affected *E. coli* reduction by HSSF (Maciel and Sabogal-Paz, 2020).

6.2. Virus

Virus adsorption in HSSF relies on chemical and electrostatic interactions between virus and the sand surface. Viruses with a lower isoelectric point (e.g., MS2) present a highly negative surface and higher repulsion by sand in neutral pH water, in contrast with viruses with higher isoelectric point (e.g., rotavirus) (Michen and Graule, 2010; Wang et al., 2016). Therefore, changes in influent water pH and composition (ions) have direct influence on viral charge and consequently on removal by HSSF.

Wang et al. (2014; 2016) showed high removal rates (> 5.00 log) of MS2 bacteriophage by HSSF in natural groundwater with a high concentration of cations (Ca^{2+} and Mg^{2+}) and pH 6.2. Moreover, in a cation-free buffer (pH 8.1), MS2 reduction of 1.20 log was observed (Wang et al., 2016).

Cation influence on viral removal was also observed by studies that changed the filter media composition. In this aspect, modifications related to enhanced virus removals include adding iron particles to the sand bed (Bradley et al., 2011), an addition of an iron nail layer (Napotnik et al., 2020), use of a zeolite layer (Adeyemo et al., 2015) and replacement of sand by crushed granite (Elliot et al., 2015).

Another factor that seems to affect viral removal is the filter media depth. Young-Rojanschi and Madramootoo (2014) observed that nearly 2.50 log removal of MS2 in a C-HSSF occurred in the first 30 cm, and approximately 0.5 log in the last 25 cm. Bradford et al. (2003) emphasize the importance of the filter media depth, providing a greater opportunity for viruses to diffuse into the sand.

Furthermore, the filter ripening also has a role in removing viruses in HSSF by increasing the residence time. Longer residence time has been described as more efficient to achieve higher virus reduction values (Napotnik et al., 2020; Wang et al. 2014; 2016; Young-Rojanschi and Madramootoo, 2014). Some authors showed a linear removal of MS2 along the sand bed in unripened filters and an exponential removal of rotavirus and MS2 according to filter depth in ripened filters (Wang et al. 2014; 2016). Another long-term study also demonstrated higher viral removal when the filter achieves full maturation (Bradley et al. 2011).

Filter maturation can contribute to enhancing virus adsorption to surfaces, and removal by predation and protease activity (Elliott et al., 2011). Indeed, the intensification of biological mechanisms in ripened filters may be responsible for virus reduction in HSSF. Elliot et al. (2011) demonstrated that suppression of microbial activity by sodium azide showed slower reduction rates of MS2 and PDR-1.

Additionally, higher idle time also enhances the chance of virus adhesion in sand, and the action of proteolytic enzymes (Elliott et al., 2011; Napotnik et al., 2020). Finally, MS2 removal was also directly correlated to influent turbidity and inversely correlated to sand size (Jenkins et al., 2011).

6.3. Protozoa

Data indicating the HSSF efficiency for protozoa removal are limited. Palmateer et al. (1999) assessed the efficiency of a biosand filter in removing *Cryptosporidium* spp. and *Giardia lamblia* (oo)cysts after one massive contamination event (10^6 and 10^5, respectively). *Cryptosporidium* spp. oocyst removal was always higher than 3.00 log, and oocysts were no longer found after 22 days. *Giardia lamblia* cysts were completely retained (removal higher than 5.00 log). Using influent waters with plausible contamination values (i.e., up to 10^3 (oo)cysts d^{-1}), removal rates of *Crytosporidium* spp. oocysts vary from 0.45 to 2.50 log, and those of *Giardia* spp. cysts vary from 1.00 to 3.00 log (Andreoli and Sabogal-Paz, 2020; Freitas et al, 2021 Medeiros et al., 2020; Terin et al., 2021).

Napotnik et al. (2020) demonstrated an average removal of oocysts of 4.00 log. The authors used I-HSSFs with different sand depths (i.e., 10, 15 and 50 cm), which did not influence protozoa removal. On the other hand, Adeyemo et al., (2015) observed poor protozoa removal rates (1.10 – 1.40 log) using an I-HSSF with a reduced filtration layer (i.e., 15 cm). This difference may be due to influent water quality in terms of protozoa, among other water quality parameters and filter design. In C-HSSFs, reducing the filter media depth from 50 cm to 25 cm also did not influence protozoa removal (Freitas et al., 2021).

6.4. Algae and Cyanobacteria

Studies on algae and cyanobacteria removal by HSSF are scarce. The first report was made by Bojcevska and Jergil (2003), which observed removal between 95-100% of the cyanobacterial biomass. Recently, Terin and Sabogal-Paz (2019) assessed the efficiency in removing *Microcysts aeruginosa* and showed an average reduction of 2.00 and 2.40 log10 by I-HSSF and C-HSSF, respectively. Unlike bacteria, an increase in HSSF performance during operation was not observed. Moreover, it was reported that 75% cyanotoxin (microcystin) removal was achieved in both filters (Terin and Sabogal-Paz, 2019).

7. Field Experiences

In 2015, more than 800 thousand BSFs had been implemented in at least 60 countries, potentially helping more than 5 million people (CAWST, 2016). Table S5 (supplementary material) presents the year and country in which the 28 field studies included in this review took place. These studies evaluated almost 1900 filters, mostly concrete and plastic BSFs. Mentions of other field studies were found by the authors, however, the lack of access to these studies' reports made them impossible to be considered in this review.

The main water quality parameters evaluated in the field studies were turbidity and bacteria removals. Due to the wide range of operational conditions (e.g., time of operation, and influent water source and quality, among others), quantification methods, and even methods to calculate and denote the results, the reported efficiencies vary considerably.

Mean turbidity removals in the field varied from <5% (Fabiszewski de Aceituno et al., 2012) to 98% (Rayner et al., 2016), with most field studies reporting removal rates above 80% (Curry et al., 2015; Duke et al., 2006; Lee, 2001; Liang et al., 2010; Mahmood et al., 2011; Rayner et al., 2016; Sisson et al., 2013a; Stauber et al., 2006; Vanderzwaag et al., 2009). HSSFs were frequently reported to be able to produce water with mean turbidity below 5 NTU (Curry et al., 2015; Duke et al., 2006; Earwaker and Webster, 2009; Hurd et al., 2001; Lee, 2001; Liang et al., 2010; Mahmood et al., 2011; Rayner et al., 2016; Sisson et al., 2013a; Stauber et al., 2006; Vanderzwaag et al., 2009), considered acceptable for household water treatment systems according to WHO (WHO, 2017). Furthermore, some HSSFs were reported to produce water with mean turbidity below 1 NTU (Hurd et al., 2001; Lee, 2001; Mahmood et al., 2011; Rayner et al., 2016; Sisson et al., 2013a; Vanderzwaag et al., 2009).

Mean bacteria removal in the field were reported to be around 1.0 log (90%), reaching 2.9 log and 3.7 log for *E. coli* and total coliform, respectively (Curry et al., 2015; Earwaker and Webster, 2009; Mahmood et al., 2011; Murphy et al., 2010a; Rayner et al., 2016; Sisson et al., 2013a; Stauber et al., 2006, 2012b, 2012a; Tiwari et al., 2009; Vanderzwaag et al., 2009). Additionally, the majority of evaluated HSSFs were able to produce water with bacteria concentration within the range considerable as acceptable for drinking water (≤ 10 CFU 100 mL^{-1}), and often reached removal of bacteria to levels below the detection limit (< 1 CFU 100mL^{-1}) (WHO, 2017). Some studies, however, reported no removal, or even increase, of bacteria concentration (including *E. coli*) after filtration (Fewster et al., 2004; Murphy et al., 2010a; Sisson et al., 2013a; Stauber et al., 2006). The main reasons were related to environmental factors (e.g., low bacteria concentration in the influent water) and incorrectly operation and/or maintenance of the HSSF (e.g., loose diffuser plate, standing water deeper than recommended, cleaning the HSSF out of routine rather than necessity) (Fewster et al., 2004; Murphy et al., 2010a; Stauber et al., 2006).

A noteworthy question raised by several of the considered field studies was the issue of recontamination of the filtered water during storage, which can considerably reduce the treatment efficiency (Curry et al., 2015; Duke et al., 2006; Fiore et al., 2010; Liang et al., 2010; Murphy et al., 2010a; Spowart, 2012; Stauber et al., 2012a). The range of recontamination went from negligible (Sisson et al., 2013a) to be observed in all HSSF systems surveyed by Spowart (2012). The absence of recontamination observed by Sisson et al. (2013a) was attributed to using chlorine as post-treatment. Recontamination events highlight that water, sanitation, and hygiene education must be combined with multi-barrier treatment interventions to provide safe water (Curry et al., 2015).

HSSF efficiencies to remove additional water quality parameters of interest were also evaluated by field studies. Lee (2001) observed that the HSSF removed, on average, 72% of H_2S producing bacteria in Nepal. Murphy et al. (2010a) reported 40 to >99% removal of iron and >97% removal of manganese by HSSF in Cambodia. The same authors reported an increase in nitrate, nitrite, and fluoride concentrations after filtration (Murphy et al., 2010a). Increases in nitrate and nitrite concentrations were also reported by Liang et al. (2010).

Evidently, operational, geographical, cultural, and other factors influenced HSSF efficiency throughout evaluated field studies; however, these studies frequently conclude that HSSF is an effective and robust option for household water treatment in rural communities. The literature shows that, after implementing HSSFs, cases of diarrhoeal diseases reduced between 47% and 74%, including among children under 5 (Aiken et al., 2011; Liang et al., 2010; Stauber et al., 2009, 2014, 2012b, 2012a; Tiwari et al., 2009). HSSF use also reduced the duration of the reported cases of diarrhoea by 1.5 days (Stauber et al., 2012b), and the overall incidence of waterborne bacterial diseases, related or not with diarrhoea, by 23% (Sheikh et al., 2016). It can be observed, however, that no significant reduction of diarrhoeal diseases was observed by Fabiszewski de Aceituno et al., (2012) following the implementation of the HSSF. Additionally, it is important to mention that the reporting bias plays a great role in studies evaluating diarrheal illness reduction due to HWTS use; and may have overestimated diarrheal reductions in the aforementioned field studies (Schmidt and Cairncross, 2009; Aiken et al., 2011). To the best of the authors' knowledge, no HSSF blind study was published to this date.

The approaches used to describe the relationship between HSSF use and water and health improvement have their limitations. A major limitation is the self-report of diarrhoeal cases, which has the potential to overestimate the reduction of cases (Aiken et al., 2011; Fabiszewski de Aceituno et al., 2012; Spowart, 2012; Stauber et al., 2012a, 2012b). Another cited limitation includes small sizes or numbers of clusters, unblinded participants, lack of a placebo, participants using other drinking water sources, and short duration of studies (Aiken et al., 2011; Fabiszewski de Aceituno et al., 2012; Rayner et al., 2016; Sheikh et al., 2016; Spowart, 2012; Stauber et al., 2012a, 2012b, 2009; Tiwari et al., 2009).

In addition to being able to produce water meeting international guidelines for drinking water quality (WHO, 2017) and improve health, the HSSFs also presented positive results regarding community acceptance and perception. Most users generally report being satisfied with the filters. The main cited reasons were cleaner water, having better taste, appearance (colour and/or opacity) and smell, easy to use and better health of family members (Duke et al., 2006; Earwaker and Webster, 2009; Fewster et al., 2004; Fiore et al., 2010; Hurd et al., 2001; Klopfenstein et al., 2011; Manz et al., 1993; Ogunyoku et al., 2011; Rayner et al., 2016; Sheikh et al., 2016; Spowart, 2012; Stauber et al., 2012b). Besides quality, water quantity is also an important aspect of a household water treatment system. In the HSSF case, users specifically reported that the filters were able to provide enough water to meet the family's needs, which varied from only drinking to bathing and washing dishes, depending on the study (Duke et al., 2006; Hurd et al., 2001; Lee, 2001; Mol, 2001; Rayner et al., 2016).

Besides the already mentioned issues, some of the more common problems reported by researchers, technicians, or users themselves were: broken parts or cracks in the filters, leading or not to leakage of water or sand and an insufficient, or lack of, education, training and, mostly, follow-up (Aiken et al., 2011; Curry et al., 2015; Duke et al., 2006; Earwaker and Webster, 2009; Fiore et al., 2010; Hurd et al., 2001; Klopfenstein et al., 2011; Mahmood et al., 2011; Ogunyoku et al., 2011; Rayner et al., 2016; Sisson et al., 2013b; Spowart, 2012; Vanderzwaag et al., 2009). Some of the less reported problems were low-quality water, ant infestation, low flow rates, use of inadequate sand, user's negative perception or dislike of the filter, incompatibility with user's lifestyle, siphoning, and problems with storage reservoir (Aiken et al., 2011;

Duke et al., 2006; Fewster et al., 2004; Fiore et al., 2010; Klopfenstein et al., 2011; Ogunyoku et al., 2011; Sisson et al., 2013b; Spowart, 2012).

The available literature shows that the sustained use of HSSF varies considerably across different experiences. While some studies reported between 85 and 100% of the HSSFs still in use, for periods of up to 8 years (Aiken et al., 2011; Duke et al., 2006; Earwaker and Webster, 2009), others showed high abandonment rates, such as 93% in Nicaragua after only 2 years (Vanderzwaag et al., 2009). According to Sisson et al. (2013b), the factors that most compromise the sustainable and effective use of HSSF includes: inadequate or insufficient education/training, poor understanding of the relationship between water quality and sanitation, inadequate water source causing filter clogging, water recontamination due to human or animal contact, cracks, low flow and inadequate maintenance (Sisson et al., 2013b). Fortunately, abandoned filters can usually be brought back into operation (Earwaker and Webster, 2009; Sisson et al., 2013b).

Earwaker and Webster (2009) argued that, in addition to the project implementation, the active and sustainable long-term adoption of HSSF depends on four interconnected elements: demand creation, maintenance, continued education, and ongoing support. To ensure that these elements are in place, support processes, such as monitoring and an adequate supply chain, are required. According to the authors, the failure of any of the four elements, or of the support processes, would prevent programs from benefiting the widest possible number of people (Earwaker and Webster, 2009).

Overall, Household Water Treatment and Safe Storage (HWTS), as the HSSF, can provide users' health benefits when used consistently and sustainably (Brown and Clasen, 2012; Enger et al., 2013). Some of the HSSF designs, such as the old BSFs, have shown high rates of user acceptability in different design settings, as previously detailed, while some of the new HSSF designs have never been field-tested. The lack of evidence of these new designs on user acceptability must be considered in further studies as, even with well-established theories, the HSSF might be rejected.

8. Concluding Remarks

HSSF is considered a feasible and low-cost technology for improving water quality (e.g., turbidity, metals, and microorganisms) in remote areas, presenting simple operation and maintenance processes. Despite this, the filter still needs further studies, especially focusing on the physicochemical processes involved in the filtering and support layers, since some elements (e.g., Fe, Al, Ca, Mg), that are present in different concentrations depending on the filter media source, can affect the filter overall efficiency. Regarding the *schmutzdecke*, there is a gap concerning its physicochemical and structural properties and their relationship with microorganisms, as well as the interrelationship between microorganisms in the biofilm. The better understanding of this microenvironment could help optimize the biological mechanism within the HSSF. Modifications to improve the HSSF efficiency are also required, particularly in topics with few studies in peer-reviewed literature, such as organic matter, nitrogen compounds, protozoa, and cyanobacteria. In addition, there are still several problems that require attention to assure a sustainable use of HSSFs in the field. Particularly, target-user education, training, and follow-up, due to its potential to prevent most of the subsequent problems. However, this issue may be complex, since it is not related to the HSSF itself, but with the HSSF implementation programs and adaptations to provide a proper end-user experience. Therefore, statements about improvements in filtered water quality/treatment performance should be weighed up in the context of possible effects on user acceptability (plus sustained use and adherence).

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References

Adeyemo, F.E.E., Kamika, I., Momba, M.N.B.N.B., 2015. Comparing the effectiveness of five low-cost home water treatment devices for Cryptosporidium, Giardia and somatic coliphages removal from water sources. Desalin. Water Treat. 56, 2351–2367.

Ahammed, M.M., Davra, K., 2011. Performance evaluation of biosand filter modified with iron oxide-coated sand for household treatment of drinking water. Desalination 276, 287–293.

Aiken, B.A., Stauber, C.E., Ortiz, G.M., Sobsey, M.D., 2011. An assessment of continued use and health impact of the concrete biosand filter in Bonao, Dominican Republic. Am. J. Trop. Med. Hyg. 85, 309–317.

Andreoli, F.C., Sabogal-Paz, L.P., 2020. Household slow sand filter to treat groundwater with microbiological risks in rural communities. Water Res. 186, 116352.

Arnold, N., Archer, A., Barkdoll, B., 2016. Bacterial adaptation and performance of household biosand water filters in differing temperatures. Water Sci. Technol. Water Supply 16, 794–801.

Avilés, M., Garrido, S.E., Esteller, M. V., De La Paz, J.S., Najera, C., Cortés, J., 2013. Removal of groundwater arsenic using a household filter with iron spikes and stainless steel. J. Environ. Manage. 131, 103–109. https://doi.org/10.1016/j.jenvman.2013.09.037

Baig, S.A., Mahmood, Q., Nawab, B., Shafqat, M.N., Pervez, A., 2011. Improvement of drinking water quality by using plant biomass through household biosand filter - A decentralized approach. Ecol. Eng. 37, 1842–1848.

Balen, D.S. 2018. Enhancing E. Coli removal from slow rate biofilters treating low carbon source waters. Master's Theses. University of New Hampshire Scholars' Repository, Durham 1229p.

Berg, M., Luzi, S., Trang, P.T.K., Viet, P.H., Giger, W., Stüben, D., 2006. Arsenic Removal from Groundwater by Household Sand Filters: Comparative Field Study, Model Calculations, and Health Benefits. Environ. Sci. Technol. 40, 5567–5573.

Barrett, J. M., Bryck, Jack, Collins, M. R., Janonis, B. A., Logsdon, G. S. 1991. Manual of Design for Slow Sand Filtration, AWWA Research Foundation, American Water Works Association, Denver, CO, USA.

Baumgartner, J., Murcott, S., Ezzati, M., 2007. Reconsidering "appropriate technology": The effects of operating conditions on the bacterial removal performance of two household drinking-water filter systems. Environ. Res. Lett. 2.

Bojcevska, H., Jergil, E., 2003. Removal of cyanobacterial toxins (LPS endotoxin and microcystin) in drinking-water using the BioSand household water filter. Minor Field Study 91 44.

Bradford, S. A., Simunek, J., Bettahar, M., Van Genuchten, M. TH., Yates, S. R. 2003. Modeling colloid attachment, straining, and exclusion in saturated porous media. Environ Sci Technol 37, 2242-2250.

Bradley, I., Straub, A., Maraccini, P., Markazi, S., Nguyen, T.H., 2011. Iron oxide amended biosand filters for virus removal. Water Res. 45, 4501–4510.

Brown, J., Clasen, T., 2012. High Adherence Is Necessary to Realize Health Gains from Water Quality Interventions. PLoS One, 7(5), e36735.

CAWST, 2012. Biosand Filter Construction Manual. Cent. Afford. Water Sanit. Technol. 2.

CAWST, 2016. Key Performance Indicators 2015; Centre for Affordable Water and Sanitation Technology: Calgary, AB.

Characklis, W.G., Marshal, K. 1990. Biofilms. First edition. Wiley-Interscience, New York, 796p.

Chiew, H., Sampson, M.L.L., Huch, S., Ken, S., Bostick, B.C., 2009. Effect of groundwater iron and phosphate on the efficacy of arsenic removal by iron-amended bios and filters. Environ. Sci. Technol. 43, 6295–6300.

Curry, K.D., Morgan, M., Peang, S.H., Seang, S., 2015. Biosand water filters for floating villages in Cambodia: Safe water does not prevent recontamination. J. Water Sanit. Hyg. Dev. 5, 213–219.

Decho, A.W. 2000. Microbial biofilms in intertidal systems: an overview. Continental Shelf Research 20:1257-1273.

Devi, R., Alemayehu, E., Singh, V., Kumar, A., Mengistie, E., 2008. Removal of fluoride, arsenic and coliform bacteria by modified homemade filter media from drinking water. Bioresour. Technol. 99, 2269–2274.

Duke, W.F., Mazumder, A. 2009. The influence of differing sand media on the performance of the biosand intermitente slow sand filter. Proc. Water Environ. Fed 14, 602 – 615.

Duke, W.F., Nordin, R.N., Baker, D., Mazumder, A., 2006. The use and performance of BioSand filters in the Artibonite Valley of Haiti: a field study of 107 households. Rural Remote Health 6, 570.

Earwaker, P., Webster, J., 2009. Evaluation of the longterm sustainability of biosand filters in rural Ethiopia. Water, Sanit. Hyg. Sustain. Dev. Multisectoral Approaches - Proc. 34th WEDC Int. Conf.

Elliott, M., Stauber, C.E., Digiano, F.A., de Aceituno, A.F., Sobsey, M.D., 2015. Investigation of E. Coli and virus reductions using replicate, bench-scale biosand filter columns and two filter media. Int. J. Environ. Res. Public Health 12, 10276–10299.

Elliott, M.A., DiGiano, F.A., Sobsey, M.D., 2011. Virus attenuation by microbial mechanisms during the idle time of a household slow sand filter. Water Res. 45, 4092–4102.

Elliott, M.A., Stauber, C.E., Koksal, F., DiGiano, F.A., Sobsey, M.D., 2008. Reductions of E. coli, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter. Water Res. 42, 2662–2670.

Elliott, M.A., Stauber, C.E., Koksal, F., Liang, K.R., Huslage, D.K., DiGiano, F.A., Sobsey, M.D., 2006. The operation, flow conditions and microbial reductions of an intermittently operated, household scale slow sand filter. IWA Publ. 1–8.

Enger, K., Nelson, K.L., Rose, J.B., Eisenberg., J.N.S., 2013. The joint effects of efficacy and compliance: A study of household water treatment effectiveness against childhood diarrhea, Water Res. 47, 1181-1190.

Fabiszewski de Aceituno, A.M., Walters, A.R., Stauber, C.E., Meza Sanchez, R.E., Sobsey, M.D., 2012. A Randomized Controlled Trial of the Plastic-Housing BioSand Filter and Its Impact on Diarrheal Disease in Copan, Honduras. Am. J. Trop. Med. Hyg. 86, 913–921.

Fewster, E., Mol, A., Wiesent-Brandsma, C., 2004. The long-term sustainability of household bio-sand filtration. People-Centred Approaches to Water Environ. Sanit. Proc. 30th WEDC Conf. 558–561.

Fiore, M.M., Minnings, K., Fiore, L.D., 2010. Assessment of biosand filter performance in rural communities in southern coastal Nicaragua: an evaluation of 199 households. Rural Remote Health 10, 1483.

Flemming, H.C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S. A., Kjelleberg, S. 2016. Biofilms: an emergent form of bacterial life. Nature Reviews Microbiology 14: 563-575.

Freitas, B.L.S., Terin, U.C., Fava, N.M.N., Sabogal-Paz, L.P. 2021. Filter media depth and its effect on the efficiency of Household Slow Sand Filter in continuous flow. J. Environ. Manage. 228:112412.

Ghebremichael, K., Wasala, L.D., Kennedy, M., Graham, N.J.D., 2012. Comparative treatment performance and hydraulic characteristics of pumice and sand biofilters for point-of-use water treatment. J. Water Supply Res. Technol.- AQUA 61, 201–209.

Guchi E. 2015. Review on Slow Sand Filtration in Removing Microbial Contamination and Particles from Drinking Water. American Journal of Food and Nutrition 3:47-55.

Haarhoff, J., Cleasby, J.L. 1991. Biological and Physical mechanisms in slow sand Filtration. In: slow sand Filtration. American Society of Civil Engineers. 34-98.

Higashi, E.S. 2016. Water toxicity bioassays from the biosand filter effluent as a tool for assessing water quality (Bioensaios de toxicidade da água do efluente de Biofiltros em areia como ferramenta de avaliação da qualidade da água). University of São Paulo doi: 10.11606/D.18.2016.tde-16092016-105143

Hijnen, W.A.M., Schijven, J.F., Bonné, P., Visser, A., Medema, G.J., 2004. Elimination of viruses, bacteria and protozoan oocysts by slow sand filtration. Water Sci. Technol. 50, 147–154.

Hsu, B. M., Huang, C. P., Pan, J. R. 2001. Filtration behaviors of Giardia and Cryptosporidium - ionic strength and pH effects. Water Res 2001, 35, 3777-3782.

Hurd, J., Lee, T.L., Paynter, N., Smith, M., 2001. Nepal Water Project.

Huisman, L., Wood, W. E. 1974. Slow sand filtration. Geneva: World Health Organization

Jenkins, M.W., Tiwari, S.K., Darby, J., 2011. Bacterial, viral and turbidity removal by intermittent slow sand filtration for household use in developing countries: Experimental investigation and modeling. Water Res. 45, 6227–6239.

Kennedy, T.J., Anderson, T.A., Hernandez, E.A., Morse, A.N., 2013. Determining the operational limits of the biosand filter. Water Sci. Technol. Water Supply 13, 56–65.

Kennedy, T.J., Hernandez, E.A., Morse, A.N., Anderson, T.A., 2012. Hydraulic loading rate effect on removal rates in a BioSand filter: A pilot study of three conditions. Water. Air. Soil Pollut. 223, 4527–4537.

Keraita, B., Drechsel, P., Konradsen, F., Vreugdenhil, R.C., 2008. Potential of simple filters to improve microbial quality of irrigation water used in urban vegetable farming in Ghana. J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 43, 749–755.

Klopfenstein, L., Petrasky, L., Winton, V., Brown, J., 2011. Addressing Water Quality Issues in Rural Cameroon with Household Biosand Filters. Int. J. Serv. Learn. Eng. Humanit. Eng. Soc. Entrep. 6, 64–80.

Kubare, M., Haarhoff, J., 2010. Rational design of domestic biosand filters. J. Water Supply Res. Technol. - AQUA 59, 1–15.

Law, S. P., Melvin, M. M., & Lamb, A. J. 2001. Visualisation of the establishment of a heterotrophic biofilm within the schmutzdecke of a slow sand filter using scanning electron microscopy. Biofilm 1:1-7.

Lee, T., 2001. Biosand household water filter project in Nepal. Massachusetts Inst. Technol.

Liang, K., Sobsey, M., Stauber, C.E., 2010. Improving household drinking water quality: use of Biosand filter in Cambodia, Water and Sanitation Program–World Bank.

Lynn, T.J., Wanjugi, P., Harwood, V.J., Ergas, S.J., 2013. Dynamic performance of biosand filters. J. Am. Water Works Assoc. 105, 71–72.

Maciel, P.M.F., Sabogal-Paz, L.P., 2020. Household slow sand filters with and without water level control: continuous and intermittent flow efficiencies. Environ. Technol. 41, 944–958.

Maeng, M., Choi, E., Dockko, S., 2015. Reduction of organic matter in drinking water using a hybrid system combined with a rock biofilter and membrane in developing countries. Int. Biodeterior. Biodegrad. 102, 223–230.

Mahaffy, N.C., Dickson, S., Cantwell, R.E., Lucier, K., Schuster-Wallace, C.J., 2015. Effects of physical disturbances on media and performance of household-scale slow sand (BioSand) filters. J. Water Supply Res. Technol. - AQUA 64, 250–259.

Mahlangu, T., Mamba, B., Momba, M., 2012. A comparative assessment of chemical contaminant removal by three household water treatment filters. Water SA 38, 39–48.

Mahmood, Q., Baig, S.A., Nawab, B., Shafqat, M.N., Pervez, A., Zeb, B.S., 2011. Development of low cost household drinking water treatment system for the earthquake affected communities in Northern Pakistan. Desalination 273, 316–320.

Manz, D. H, Buzinus, B.J., Morales, C., 1993. Final Report on the Nicaragua houshold water supply and testing project. Calgary, AB, Canada.

Manz, D. H., 2004. New Horizons for Slow Sand Filtration. In: The Eleventh Canadian Conference and Second Policy Forum on Drinking Water and the Biennial Conference of the Federal-Provincial-Territorial Committee on Drinkig Water, Promoting Public Health Through Safe Drinking Water, Abril 3-6, Calgary, Canada, p. 682-692.

McKenzie, E.R., Jenkins, M.W., Tiwari, S.S.K., Darby, J., Saenyi, W., Gichaba, C.M., 2013. In-home performance and variability of Biosand filters treating turbid surface and rain water in rural Kenya. J. Water Sanit. Hyg. Dev. 3, 189–198.

Medeiros, R.C., de, N., Freitas, B.L.S., Sabogal-Paz, L.P., Hoffmann, M.T., Davis, J., Fernandez-Ibañez, P., Byrne, J.A., 2020. Drinking water treatment by multistage filtration on a household scale: Efficiency and challenges. Water Res. 178.

Michen, B., Graule, T., 2010. Isoelectric points of viruses. Journal of Applied Microbiology 109 (2), 388e397.

Mol, A., 2001. Targeting individuals: away from the concept of community involvement - The success of household sand filtration. Waterlines, Int. J. Appropr. Technol. water supply Sanit. 20.

Murphy, H.M., McBean, E.A., Farahbakhsh, K., 2010a. A critical evaluation of two point-of-use water treatment technologies: Can they provide water that meets WHO drinking water guidelines? J. Water Health 8, 611–630.

Mwabi, J.K., Adeyemo, F.E., Mahlangu, T.O., Mamba, B.B., Brouckaert, B.M., Swartz, C.D., Offringa, G., Mpenyana-Monyatsi, L., Momba, M.N.B., 2011. Household water treatment systems: A solution to the production of safe drinking water by the low-income communities of Southern Africa. Phys. Chem. Earth 36, 1120–1128.

Mwabi, J.K., Mamba, B.B., Momba, M.N.B., 2013. Removal of waterborne bacteria from surface water and groundwater by cost-effective household water treatment systems (HWTS): A sustainable solution for improving water quality in rural communities of Africa. Water SA 39, 445–456.

Mwabi, J.K., Mamba, B.B., Momba, M.N.B., 2012. Removal of escherichia coli and faecal coliforms from surface water and groundwater by household water treatment devices/systems: A sustainable solution for improving water quality in rural communities of the southern african development community region. Int. J. Environ. Res. Public Health 9, 139–170.

Nair, A.T., Ahammed, M.M., Davra, K., 2014. Influence of operating parameters on the performance of a household slow sand filter. Water Supply 14, 643–649.

Nakamoto, N., Graham, N., Collins, M.R., Gimbel, R. 2014. Progress in slow sand and alternative biofiltration process–further developments and applications. IWA publishing. 584p.

Napotnik, J.A., Baker, D., Jellison, K.L., 2017. Effect of Sand Bed Depth and Medium Age on Escherichia coli and Turbidity Removal in Biosand Filters. Environ. Sci. Technol. 51, 3402–3409.

Napotnik, J.A., Baker, D., Jellison, K.L., 2020. Influence of sand depth and pause period on microbial removal in traditional and modified biosand filters. Water Res. 116577.

Nasser Fava, N. de M., Terin, U.C., Freitas, B.L.S., Sabogal-Paz, L.P., Fernandez-Ibañez, P., Anthony Byrne, J., 2020. Household slow sand filters in continuous and intermittent flows and their efficiency in microorganism's removal from river water. Environ. Technol. 0, 1–10.

Ngai, T.K.K., 2014. Global Review of the Adoption, Use, and Performance of the Biosand Filter, in: Nakamoto, N., Graham, N., Collins, R.M., Gimbel, R. (Eds.), Progress in Slow Sand And Alternative Biofiltration Processes: Further Developments and Applications. IWA Publishing, London, UK, pp. 309–317.

Ngai, T.K.K., Baker, D.L., 2014. Recent advances in household biosand filter design, in: Nakamoto, N., Graham, N., Collins, M.R., Gimbel, R. (Eds.), Progress in Slow Sand and Alternative Biofiltration Processes: Further Developments and Applications. IWA Publishing, London, UK, pp. 319–330.

Ngai, T.K.K., Shrestha, R.R., Dangol, B., Maharjan, M., Murcott, S.E., 2007. Design for sustainable development - Household drinking water filter for arsenic and pathogen treatment in Nepal. J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 42, 1879–1888.

Ogunyoku, T.A., Nover, D.M., McKenzie, E.R., Joshi, G., Fleenor, W.E., 2011. Point-Of-Use Drinking Water Treatment in the Developing World: Community Acceptance, Project Monitoring and Revision. Int. J. Serv. Learn. Eng. Humanit. Eng. Soc. Entrep. 6, 14–32.

Outhwaite, R., Campos, L.C., 2010. Individual Environmental Systems Project - Optimisation of Household scale Biosand Filters.

Palmateer, G., Manz, D., Jurkovic, A., McInnis, R., Unger, S., Kwan, K.K., Dutka, B.J., 1999. Toxicant and parasite challenge of Manz intermittent slow sand filter. Environ. Toxicol. 14, 217–225.

Pompei, C.M.E., Ciric, L., Canales, M., Karu, K., Vieira, E.M., Campos, L.C., 2017. Influence of PPCPs on the performance of intermittently operated slow sand filters for household water purification. Sci. Total Environ. 581–582, 174–185.

Pompei, C.M.E., Campos, L.C., da Silva, B.F., Fogo, J.C., Vieira, E.M., 2019. Occurrence of PPCPs in a Brazilian water reservoir and their removal efficiency by ecological filtration. Chemosphere 226, 210–219.

Ranjan, P., Prem, M. 2018. Schmutzdecke - A Filtration Layer of Slow Sand Filter. International Journal of Current Microbiology and Applied Sciences 7:637-645.

Rayner, J., Murray, A., Joseph, M., Branz, A., Lantagne, D., 2016. Evaluation of household drinking water filter distribution programs in Haiti. J. Water Sanit. Hyg. Dev. 6, 42–54.

Ribalet, F., Intertaglia, L., Lebaron, P., Casotti, R. 2008. Differential effect of three polyunsaturated aldehydes on marine bacterial isolates. Aquatic Toxicology 86: 249-255.

Romero, D.A.D., de Almeida Silva, M.C., Chaúque, B.J.M., Benetti, A.D., 2020. Biosand filter as a point-of-usewater treatment technology: Influence of turbidity on microorganism removal efficiency. Water (Switzerland) 12.

Sabogal-Paz, L.P., Campos, L.C., Bogush, A., Canales, M., 2020. Household slow sand filters in intermittent and continuous flows to treat water containing low mineral ion concentrations and Bisphenol A. Sci. Total Environ. 702, 135078.

Sauer, K., Camper, A.K., Ehrlich, G.D., Costerton, J.W., Davies, D.G. Pseudomonas aeruginosa Displays Multiple Phenotypes during Development as a Biofilm. Journal of Bacteriology 184: 1140-1154.

Schijven, J. F., de Bruin, H. A. M., Hassanizadeh, S. M., de Roda Husman, A. M., 2003. Bacteriophages and clostridium spores as indicator organisms for removal of pathogens by passage through saturated dune sand. Water Res 37 (9), 2186–2194.

Sheikh, M.A., Mustufa, M.A., Laghari, T.M., Manzoor, B., Haider, S.A., Bibi, S., Ali, F.I., 2016. Prevalence of waterborne diseases in exposed and unexposed clusters using biosand filters in a rural community, Sindh, Pakistan. Expo. Heal. 8, 193–198.

Singer, S., Skinner, B., Cantwell, R.E., 2017. Impact of surface maintenance on BioSand filter performance and flow. J. Water Health 15, 262–272.

Siqueira-Castro, I.C.V., Greinert-Goulart, J.A., Bonatti, T.R., Yamashiro, S., Franco, R.M.B., 2016. First report of predation of Giardia sp. cysts by ciliated protozoa and confirmation of predation of Cryptosporidium spp. oocysts by ciliate species. Environ. Sci. Pollut. Res. 23, 11357–11362.

Sisson, A.J., Wampler, P.J., Rediske, R.R., McNair, J.N., Frobish, D.J., 2013a. Long-term field performance of biosand filters in the Artibonite Valley, Haiti. Am. J. Trop. Med. Hyg. 88, 862–867.

Sisson, A.J., Wampler, P.J., Rediske, R.R., Molla, A.R., 2013b. An assessment of long-term biosand filter use and sustainability in the Artibonite Valley near Deschapelles, Haiti. J. Water Sanit. Hyg. Dev. 3, 51–60.

Sizirici, B., Yildiz, I., AlAli, A., Alkhemeiri, A., Alkhoori, A., Bufalasa, F., Alawadi, R., 2019. Modified biosand filters enriched with iron oxide coated gravel to remove chemical, organic and bacteriological contaminants. J. Water Process Eng. 27, 110–119.

Smith, A.W., 2013. Sandstorm: A biosand filter designed for small-scale enterprises. 36th WEDC Int. Conf. Deliv. Water, Sanit. Hyg. Serv. an Uncertain Environ. 0–6.

Smith, K., Li, Zhenyu, Chen, B., Liang, H., Zhang, X., Xu, R., Li,Zhilin, Dai, H., Wei, C., Liu, S., 2017. Comparison of sand-based water filters for point-of-use arsenic removal in China. Chemosphere 168, 155–162.

Snyder, K. V., Webster, T.M., Upadhyaya, G., Hayes, K.F., Raskin, L., 2016. Vinegar-amended anaerobic biosand filter for the removal of arsenic and nitrate from groundwater. J. Environ. Manage. 171, 21–28.

Song, S., Rong, L., Dong, K., Liu, X., Le Clech, P., Shen, Y. 2020. Particle-scale modelling of fluid velocity distribution near the particles surface in sand filtration. Water Res 177, 115758.

Souza Freitas, B.L., Sabogal-Paz, L.P., 2020. Pretreatment using Opuntia cochenillifera followed by household slow sand filters: technological alternatives for supplying isolated communities. Environ. Technol. 41, 2783–2794.

Spowart, M., 2012. Educational Concerns of Implementing Biosand Water Filters in Rural Uganda. Dominican University of California, San Rafael, California.

Stauber, C.E., Elliot, M.A., Koksal, F., Ortiz, G.M., DiGiano, F.A., Sobsey, M.D., Elliott, M.A., Koksal, F., Ortiz, G.M., DiGiano, F.A., Sobsey, M.D., 2006. Characterisation of the biosand filter for E. coli reductions from household drinking water under controlled laboratory and field use conditions. Water Sci. Technol. 54, 1–7.

Stauber, C.E., Kominek, B., Liang, K.R., Osman, M.K., Sobsey, M.D., 2014. Correction: Stauber, C.E., et al. Evaluation of the Impact of the Plastic BioSand Filter on Health and Drinking Water Quality in Rural Tamale, Ghana. Int. J. Environ. Res. Public Health 2012, 9, 3806-3823. Int. J. Environ. Res. Public Heal. 11, 9154–9155.

Stauber, C.E., Kominek, B., Liang, K.R., Osman, M.K., Sobsey, M.D., 2012a. Evaluation of the impact of the plastic biosand filter on health and drinking water quality in rural tamale, Ghana. Int. J. Environ. Res. Public Health 9, 3806–3823.

Stauber, C.E., Ortiz, G.M., Loomis, D.P., Sobsey, M.D., 2009. A Randomized Controlled Trial of the Concrete Biosand Filter and Its Impact on Diarrheal Disease in Bonao, Dominican Republic. Am. J. Trop. Med. Hyg. 80, 286–293.

Stauber, C.E., Printy, E.R., McCarty, F.A., Liang, K.R., Sobsey, M.D., 2012b. Cluster randomized controlled trial of the plastic BioSand water filter in Cambodia. Environ. Sci. Technol. 46, 722–728.

Terin, U.C., Freitas, B.L.S., Fava, N.M.N., Sabogal-Paz, L.P. 2021. Evaluation of a multi-barrier household system as an alternative to surface water treatment with microbiological risks. Environ. Technol.

Terin, U.C., Sabogal-Paz, L.P., 2019a. Microcystis aeruginosa and microcystin-LR removal by household slow sand filters operating in continuous and intermittent flows. Water Res. 150.

Tiwari, S.S.K., Schmidt, W.P., Darby, J., Kariuki, Z.G., Jenkins, M.W., 2009. Intermittent slow sand filtration for preventing diarrhoea among children in Kenyan households using unimproved water sources: Randomized controlled trial. Trop. Med. Int. Heal. 14, 1374–1382.

Treumann, S., Torkzaban, S., Bradford, S. A., Visalakshan, R. M., Page, D. 2014. An explanation for differences in the process of colloid adsorption in batch and column studies. J. Contam Hydrol 164, 219-229.

Triple-Quest, 2010. Hydraid BioSand Water Filter Installation Manual. The Dow Chemical Company, Grand Rapids, MI, USA.

Tufenkji, N., Elimelech, M. 2004. Correlation equation for predicting single-collector efficiency in physicochemical filtration in saturated porous media. Environ Sci Technol, 38, 529-536.

Tufenkji, N., Miller, G. F., Ryan, J. N., Harvey, R. W., Elimelech, M. 2004. Transport of Cryptosporidium oocysts in porous media: role of straining and physicochemical filtration. Environ Sci Technol 38, 5932–5938.u

Vanderzwaag, J.C., Atwater, J.W., Bartlett, K.H., Baker, D., 2009. Field evaluation of long-term performance and use of biosand filters in Posoltega, Nicaragua. Water Qual. Res. J. Canada 44, 111–121.

Wakelin, S., Page, D., Dillon, P., Pavelic, P., Abell, G.C.J., Gregg, A.L., Brodie, E., DeSantis, T.Z., Goldfarb, K.C., Anderson, G., 2011. Microbial community structure of a slow sand filter schmutzdecke: A phylogenetic snapshot based on rRNA sequence analysis. Water Sci. Technol. Water Supply 11, 426–436.

Wang, H., Li, M., Brockman, K., Nguyen, T.H., 2016. Reduction of MS2 bacteriophage and rotavirus in biosand filters. Environ. Sci. Water Res. Technol. 2, 483–491.

Wang, H., Narihiro, T., Straub, A.P., Pugh, C.R., Tamaki, H., Moor, J.F., Bradley, I.M., Kamagata, Y., Liu, W.T., Nguyen, T.H., 2014. MS2 bacteriophage reduction and microbial communities in biosand filters. Environ. Sci. Technol. 48, 6702–6709.

Weber-Shirk, M. L. 2002. Enhancing slow sand filter performance with an acid-soluble seston extract. Water Res 36, 4753-4756.

Weber-Shirk, M. L., Chan, K. L. 2007. The role of aluminum in slow sand filtration. Water Res 41, 1350-1354.

Weber-Shirk, M.L., Dick, R.I., 1997a. Physical-Chemical Mechanisms in Slow Sand Fil- ters. J. Am. Water Works Assoc. 89, 87–100.

WHO, 2017. Guidelines for drinking-water quality, 4th edition, incorporating the 1st addendum.

Wichard, T., Poulet, S.A., Pohnert, G. 2005. Determination and quantification of alpha,beta,gamma,delta-unsaturated aldehydes as pentafluorobenzyl-oxime derivates in diatom cultures and natural phytoplankton populations: application in marine field studies. Journal of Chromatography B-Analytical Technologies in the Biomedical and Life Sciences 814:155-161.

Yildiz, B.S., 2016. Performance assessment of modified biosand filter with an extra disinfection layer. J. Water Supply Res. Technol. - AQUA 65, 266–276.

Young-Rojanschi, C., Madramootoo, C., 2014. Intermittent versus continuous operation of biosand filters. Water Res. 49, 1–10. https://doi.org/10.1016/j.watres.2013.11.011

Young-Rojanschi, C., Madramootoo, C., 2015. Comparing the performance of biosand filters operated with multiday residence periods. J. Water Supply Res. Technol. - AQUA 64, 157–167.

Supplementary Material

A Critical Overview of Household Slow Sand Filters for Water Treatment

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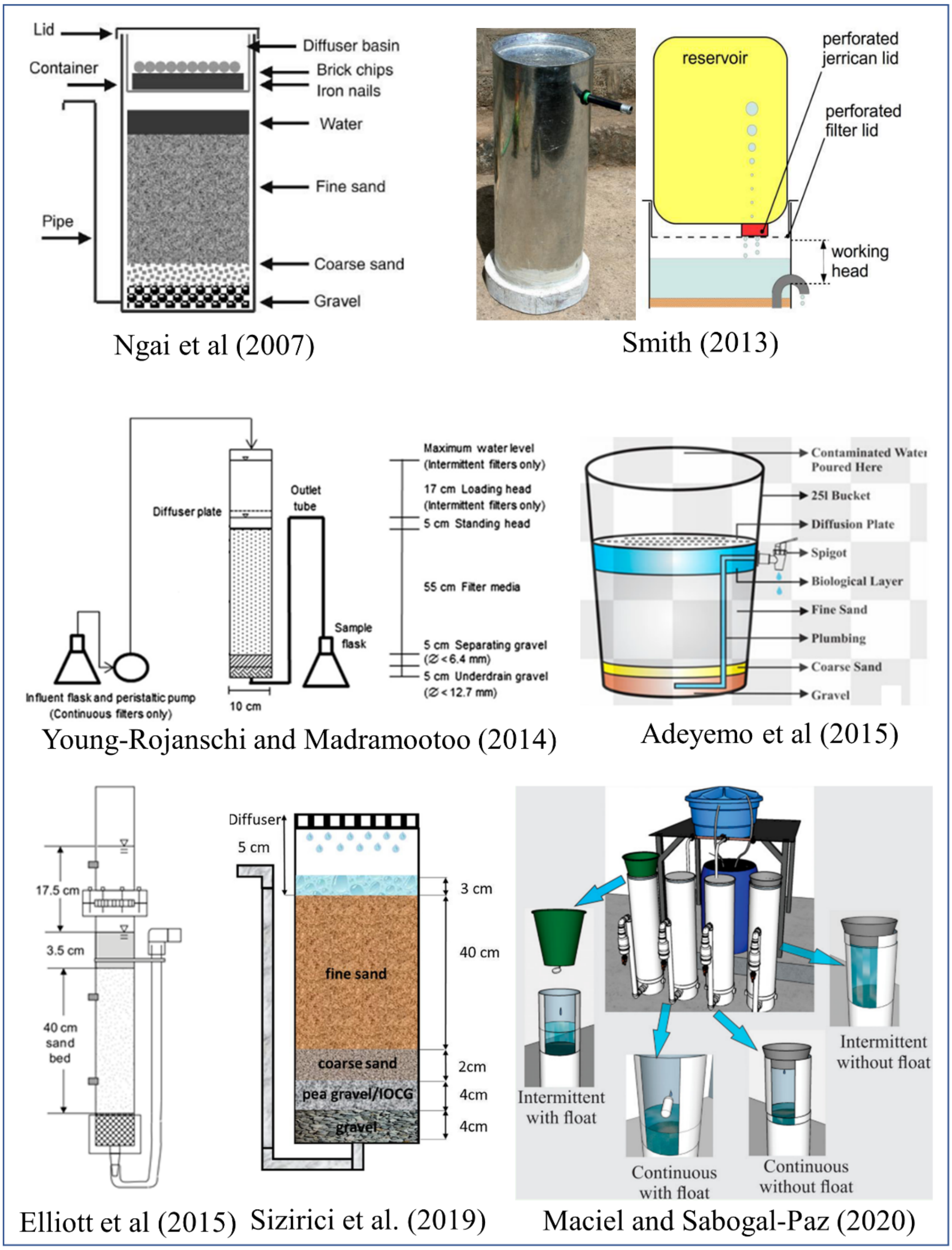
Figure S1 – Different examples of HSSF design projects



Ngai et al (2007)

Smith (2013)

Young-Rojanschi and Madramootoo (2014)

Adeyemo et al (2015)

Elliott et al (2015)

Sizirici et al. (2019)

Maciel and Sabogal-Paz (2020)

Figure S2 – Intermittent (a) and continuous (b) HSSF design. Continuous HSSF requires bigger infrastructure and occupies more area compared to intermittent.

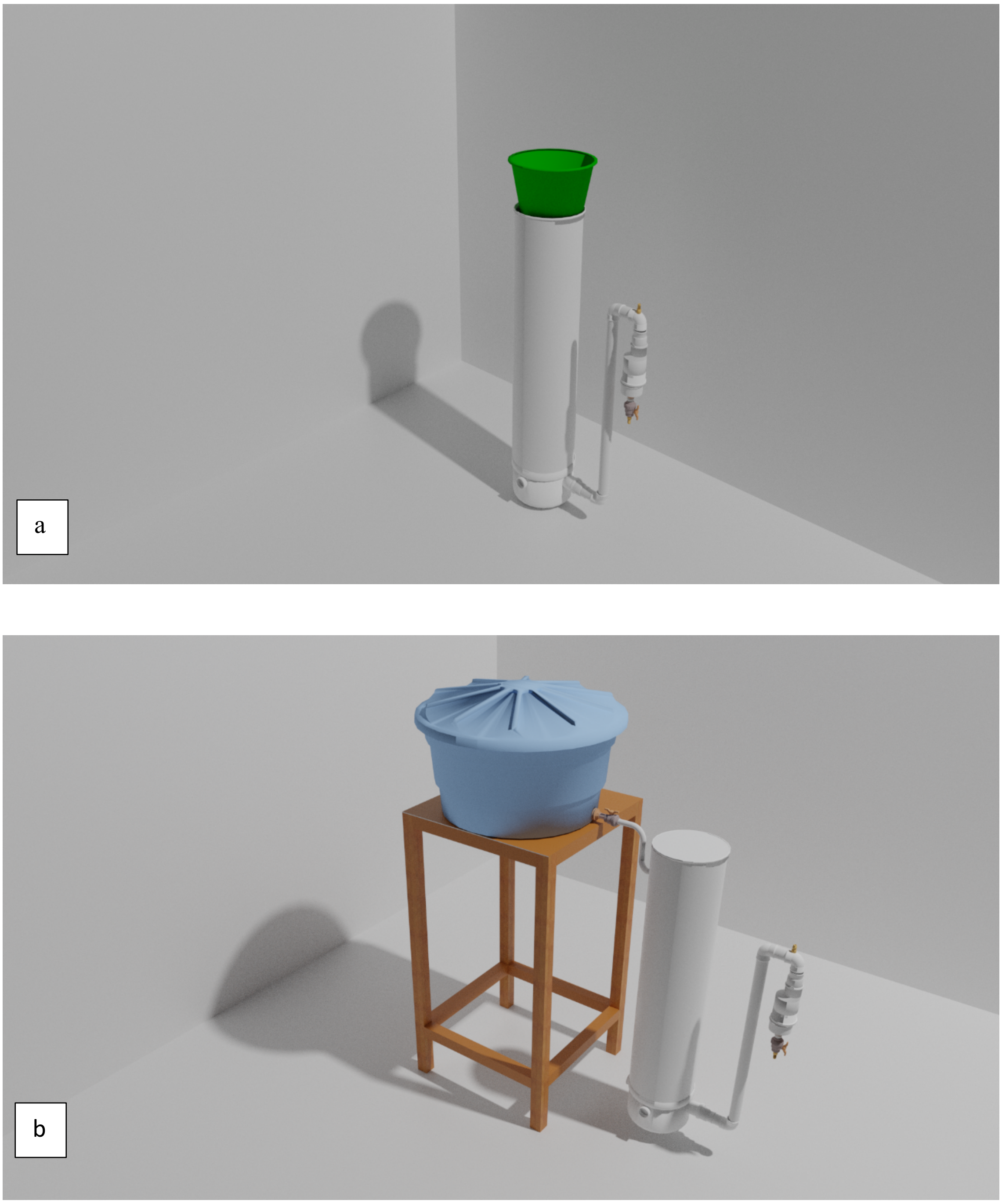


Table S1 – Cleaning methods reported in the literature of household slow sand filters.

Cleaning method	References
Surface agitation and/or replacement (< 1 cm of the sand layer)	Mondal et al (2007), CAWST (2012), Kennedy et al. (2012); Kennedy et al. (2013), Mahaffy et al. (2015), Elliott et al. (2015), Maciel and Sabogal-Paz (2018), Nasser Fava et al. (2020), Medeiros et al. (2020), Freitas et al. (2021), Terin et al. (2021)
Stirring and/or replacement > 1 cm of the sand layer	Ahammed and Davra (2011), Ngai et al (2007), Nair et al. (2014), Sheikh et al. (2016), Singer et al. (2017)
Wet harrowing - gently rub off the sand top and wait for clogging material to settle	Tiwari et al (2009), Jenkins et al. (2011), Mckenzie et al. (2013)
Felt blanket cleaning	Maciel and Sabogal-Paz (2020), Souza Freitas and Sabogal-Paz (2019), Nasser Fava et al. (2020), Medeiros et al. (2020), Sabogal-Paz et al. (2020), Freitas et al. (2021), Terin et al. (2021)

Table S2 - Household slow sand filter process parameters presented in the literature

Reference	Scale of study	Peak of filtration rate (m h^{-1})	Feeding volume (L)	Pause period (h)
(Ahammed and Davra, 2011)	Full scale	0.45 (I)	20	24**
(Arnold et al., 2016)	Column study	1.33 (I)	1	24**
(Baig et al., 2011)	Full scale	1.49 (I)	20	24**
(Baumgartner et al., 2007)	Full scale	N/A^{+}	20 and 10	12, 24 and 36
(Bradley et al., 2011)	Full scale	0.71 (I)	20	24**
(Chan et al., 2015)	Full scale	0.30* (I)	12	Not informed (dosed twice a day)
(Elliott et al., 2008)	Full scale	0.75* (I)	20 and 40	24**

(Elliott et al., 2015)	Column study	0.80 (I)	0.43 and 0.45	24**
(Souza Freitas and Sabogal-Paz, 2019)	Full scale	0.12 (I) and 0.05 (C)	15	12* and 4*
(Ghebremichael et al., 2012)	Column study	0.67 (I)	2.5, 2.7, and 3.0	1.5, 4, 20, 22.5, and 72.
(Jenkins et al., 2011)	Full scale	0.39 (I)	20, twice a day	16 and 5
(Kennedy et al., 2012)	Full scale	N/A+	20	22
(Kennedy et al., 2013)	Full scale	N/A+	20	One daily dosing
(Lynn et al., 2013)	Full scale	0.52* (I)	20, (10 + 10 after the level lowed)	20** - 24**
(Maciel and Sabogal-Paz, 2020)	Full scale	0.21 (I) and 0.028 (C)	16	16**
(Mahaffy et al., 2015)	Full scale	N/A+	9.0 and 7.2	24**
(Nair et al., 2014)	Full scale	0.80* (I)	20 and 40	1**, 12** and 24**
(Napotnik et al., 2017)	Full scale	<0.5 (I)	12; 3.6 and 1.5	3**
(Sabogal-Paz et al., 2020)	Column study	0.87 (I) and 0.02 (C)	1	8**
(Sizirici et al., 2019)	Column study	1.51* (I)	0,7	12**
(Smith, 2013)	Full scale	0.20 (I)	20	twice a day
(Terin and Sabogal-Paz, 2019)	Full scale	0.13 (I) and 0.051 (C)	15	4** and 12**
(Terin et al., 2021)	Full scale	9.0 (I) and 12.0 (I)	16	2.67 and 11.67
(Yildiz, 2016)	Column study	0.45* (I)	8	12**
(Young-Rojanschi and Madramootoo, 2014)	Column study	0.69 (I) and 0.01 (C)	2.0	24**

(Young-Rojanschi and Madramootoo, 2015)	Column study	0.72 (I)	1.8	24, 48 and 72

Note: $^{+}$Filtration rate was not informed, or it was not presented sufficient data to be calculated, * Filtration rate calculated according to information extracted from the paper; ** the informed pause period was related to time between fills, and not effective pause.

Table S3 - Average physicochemical parameters removal by HSSF in drinking water.

Parameter	**Average removal range (%)**	**References**
Turbidity	≤ 50%	Mwabi et al. (2013); Adeyemo et al. (2015); Young-Rojanschi e Madramootoo (2015); Arnold et al. (2016); Andreoli e Sabogal-Paz (2020); Medeiros et al. (2020)
	50% - 75%	Elliott et al. (2008); Mwabi et al. (2013); Adeyemo et al. (2015); Young-Rojanschi e Madramootoo (2015); Napotnik et al. (2017); Freitas et al. (2021); Terin et al. (2021)
	75% - 90%	Stauber et al. (2006); Murphy et al. (2010a); Jenkins et al. (2011); Mahlangu et al. (2012); Mwabi et al. (2012); Kennedy et al. (2013); Lynn et al. (2013); Mwabi et al. (2013); Young-Rojanschi e Madramootoo (2014); Mahaffy et al. (2015); Tundia et al. (2016); Yildiz (2016); Napotnik et al. (2017); Faria Maciel e Sabogal-Paz (2018); Terin e Sabogal-Paz (2018); Souza Freitas e Sabogal-Paz (2019)
	> 90%	Murphy et al. (2010a); Murphy et al. (2010b); Ahammed e Davra (2011); Kennedy et al. (2012); Mwabi et al. (2012); Mwabi et al. (2013); Nair et al. (2014); Young-Rojanschi e Madramootoo (2014); Adeyemo et al. (2015); Mahaffy et al. (2015); Tundia et al. (2016); Singer et al. (2017); Faria Maciel e Sabogal-Paz (2018); Sizirici et al. (2019)

Organic Matter		≤ 10%	Bradley et al. (2011); Napotnik et al. (2017); Terin and Sabogal-Paz (2019); Freitas et al., (2021); Terin et al. (2021)
		10% - 50%	Mahlangu et al. (2012); Lynn et al. (2013); Ghebremichael et al. (2016); Souza Freitas and Sabogal-Paz (2019); Sizirici et al. (2019); Andreoli and Sabogal-Paz (2020); Terin et al. (2021)
		75% - 90%	Maeng et al. (2015)
Metals	Mercury	> 90%	Palmateer et al. (1999)
	Arsenic	≤ 75%	Chiew et al. (2009); Snyder et al. (2016); Mahlangu et al. (2012); Mwabi et al. (2011)
		75% - 90%	Berg et al. (2006)
		> 90%	Ngai et al. (2007); Devi et al. (2008); Avilés et al. (2013); Smith et al. (2017)
	Iron	50% - 75%	Mahlangu et al. (2012)
		75% - 90%	Mwabi et al. (2011); Nitzsche et al. (2015)
		> 90%	Ngai et al. (2007)
	Phosphate	< 50%	Mwabi et al. (2011)
		90%	Berg et al. (2006)
	Fluoride	≤ 50%	Mahlangu et al. (2012); Mwabi et al. (2011)
		75% - 99%	Devi et al. (2008); Mwabi et al. (2011)
	Calcium	< 50%	Mwabi et al. (2011)

		> 90%	Mwabi et al. (2011)
	Magnesium	≤ 55%	Mwabi et al. (2011); Mahlangu et al. (2012)
Nitrogen compounds	Nitrate	≤ 53%	Mwabi et al. (2011); Kennedy et al. (2012); Mahlangu et al. (2012); Avilés et al. (2013); Romero et al. (2020)
		> 90%	Snyder et al. (2016)
Emerging Pollutants	Herbicide/ Pesticide	≤ 50%	Outhwaite & Campos (2010)
		50% - 99%	Palmateer et al. (1999)*
	Pharmaceutical compounds	70 - 99%	Pompei et al. (2017); Pompei et al. (2019)
	Endocrine disruptors	≤ 20%	Kennnedy et al. (2013); Sabogal-Paz et al. (2020)

Note: *Cumulative percent retention.

Table S4 - Average microbial removal by HSSF in drinking water.

Microorganism group	**Average removal range (log)**	**References**
Bacteria	≤ 1.00	(Ahammed and Davra, 2011; Andreoli and Sabogal-Paz, 2020; Baig et al., 2011; Elliott et al., 2008; Maciel and Sabogal-Paz, 2020; Medeiros et al., 2020; Murphy et al., 2010a, 2010b; Yildiz, 2016)

	E. coli	1.00 – 2.00	(Ahammed and Davra, 2011; Andreoli and Sabogal-Paz, 2020; Elliott et al., 2008, 2015; Freitas et al., 2021; Ghebremichael et al., 2012; Lynn et al., 2013; Maciel and Sabogal-Paz, 2020; Medeiros et al., 2020; Murphy et al., 2010a, 2010b; Mwabi et al., 2012; Napotnik et al., 2020; Singer et al., 2017; Sizirici et al., 2019; Souza Freitas and Sabogal-Paz, 2020; Stauber et al., 2006; Terin et al. 2021; Young-Rojanschi and Madramootoo, 2014, 2015)
		2.00 – 3.00	(Ahammed and Davra, 2011; Andreoli and Sabogal-Paz, 2020; Elliott et al., 2008, 2015; Freitas et al., 2021; Maciel and Sabogal-Paz, 2020; Medeiros et al., 2020; Mwabi et al., 2012; Nair et al., 2014; Napotnik et al., 2020; Singer et al., 2017; Souza Freitas and Sabogal-Paz, 2020; Yildiz, 2016)
		3.00 – 4.00	(Andreoli and Sabogal-Paz, 2020; Mwabi et al., 2012; Napotnik et al., 2017, 20207; Souza Freitas and Sabogal-Paz, 2020; Young-Rojanschi and Madramootoo, 2014)
	Total coliforms	0.33 – 5.50	(Arnold et al., 2016; Baig et al., 2011; Chan et al., 2015; Elliott et al., 2008; Freitas et al., 2021; Lynn et al., 2013; Napotnik et al., 2020; Sizirici et al., 2019; Terin et al., 2021; Yildiz, 2016)
	Fecal coliforms	0.48 – 3.70	(Ahammed and Davra, 2011; Jenkins et al., 2011; Kennedy et al., 2012, 2013a; Mwabi et al., 2012)
	Vibrio cholerae	0.46 – 4.80	(Mwabi et al., 2013; Thomson and Gunsch, 2015)
	Salmonella typhimurium	1.30 – 3.40	(Mwabi et al., 2013)

	Shingella dysenteriae	0.60 – 3.70	(Mwabi et al., 2013)
Viruses	MS2	0.38 – ≥ 4.00	(Bradley et al., 2011; Elliott et al., 2006, 2011, 2015; Jenkins et al., 2011; Napotnik et al., 2020; Wang et al., 2014, 2016; Young-Rojanschi and Madramootoo, 2014)
	Somatic coliphage	0.57 – 1.43	(Adeyemo et al., 2015)
	PRD-1	0.30 - ≤1.00	(Elliott et al., 2006, 2008, 2011, 2015)
	Echovirus 12	1.30 – 2.21	(Elliott et al., 2006, 2015)
	Rotavirus	3.54 – 4.92	(Wang et al., 2016)
Protozoa	*Cryptosporidium* oocysts	1.20 – 4.80	(Adeyemo et al., 2015; Andreoli and Sabogal-Paz, 2020; Freitas et al., 2021; Medeiros et al., 2020; Napotnik et al., 2020; Palmateer et al., 1999; Terin et al., 2021)
	Giardia cysts	1.15 – ≥ 5.00	(Adeyemo et al., 2015; Andreoli and Sabogal-Paz, 2020; Freitas et al., 2021; Medeiros et al., 2020; Napotnik et al., 2020; Palmateer et al., 1999; Terin et al., 2021)
Cyanobacteria	*Microcystis aeruginosa*	1.99 – 2.40	(Terin and Sabogal-Paz, 2019)

Table S5 - Summary of published field studies.

Country	Year(s)	Reference
Cambodia	2010, 2012, 2015	(Liang et al., 2010; Murphy et al., 2010; Stauber et al., 2012b; Curry et al., 2015)
Cameroon	2011	(Klopfenstein et al., 2011)
Dominican Republic	2006, 2009, 2011	(Stauber et al., 2006; Stauber et al., 2009; Aiken et al., 2011)
Ethiopia	2009	(Earwaker and Webster, 2009)
Ghana	2012	(Stauber et al., 2014, 2012a)
Haiti	2006, 2013, 2016	(Duke et al., 2006; Sisson et al., 2013b; Rayner et al., 2016)
Honduras	2012	(Fabiszewski de Aceituno et al., 2012)
Kenya	2001, 2004, 2009	(Mol, 2001; Fewster et al., 2004; Tiwari et al., 2009)
Nepal	2001	(Hurd et al., 2001*; Lee, 2001*)
Nicaragua	1993, 2009, 2010	(Manz et al., 1993*; Vanderzwaag et al., 2009; Fiore et al., 2010)
Pakistan	2011, 2016	(Mahmood et al., 2011; Sheikh et al., 2016)
Uganda	2011, 2012	(Ogunyoku et al., 2011; Spowart, 2012)*

Note: *not peer-reviewed literature.

Additional references

Bellamy, W.D., Hendricks, D.W., Logsdon, G.S., 1985. Slow Sand Filtration: Influences of Selected Process Variables. J. Am. Water Works Assoc. 77, 62–66.

Calixto, K.G. Sabogal-Paz, L.P., Pozzi, E., Campos, L.C. 2020. Ripening of household slow sand filter by adding fish Food. J. Water Sanit. Hyg. Dev., 143

Chan, C.C.V., Neufeld, K., Cusworth, D., Gavrilovic, S., Ngai, T., 2015. Investigation of the Effect of Grain Size, Flow Rate and Diffuser Design on the

CAWST Biosand Filter Performance. Int. J. Serv. Learn. Eng. Humanit. Eng. Soc. Entrep. 10, 1–23.

Davies, C. M., Kaucner, C., Altavilla, N., Ashbolt, N. J., Ferguson, C. M., Krogh, M., Hijnen, W. A. M., Medema, G. J., Deere, D. A. 2005. Fate and Transport of Surface Water Pathogens in Watersheds. Awwa Research Foundation, Denver, US.

Emelko, M.B. (2001). Removal of Cryptosporidium parvum by granular media filtration. Thesis, University of Waterloo, Ontario, Canada.

Fogler, H.S., 1999. Elements of Chemical Reaction Engineering, 3rd ed. Printice-Hall, Inc, New Jersy.

Hijnen, W.A. M., Dullemont, Y. J., Schijven, J. F., Hanzens-Brouwer, A. J., Rosielle, M., Medema, G. 2007. Removal and fate of Cryptosporidium parvum, Clostridium perfringens and small-sized centric diatoms (Stephanodiscus hantzschii) in slow sand filters. Water Res 41, 2151-2162.

Mondal, P.K., Seth, R., Biswas, N. 2007. Performance evaluation of fabric aided slow sand filter in drinking water treatment. Journal of Environmental Engineering and Science.

Murphy, H.M., McBean, E.A., Farahbakhsh, K., 2010b. Nitrification, denitrification and ammonification in point-of-use biosand filters in rural Cambodia. J. Water Health 8, 803–817.

Napotnik, J. A., Jellison, K. L., 2014. Transport effects on hydraulics loading rate and microbial removal performance in biosand filters. J Water Health 12 (4), 686-691.

Schuler, P. F., Ghosh, M. M., Gopalan, P. 1991. Slow sand and diatomaceous earth filtration of cysts and other particulates. Water Res 25 (8), 995-1005.

Thomson, A.A., Gunsch, C.K., 2015. Evaluation of a field appropriate membrane filtration method for the detection of vibrio cholerae for the measurement of biosand filter performance in the artibonite valley, haiti. Environ. Monit. Assess. 187.

Tufenkji, N., Elimelech, M. 2005. Spatial distributions of Cryptosporidium oocysts in porous media: evidence for dual mode deposition. Environ Sci Technol 39, 3620-3629.

Tundia, K.R., Ahammed, M.M., George, D., 2016. The effect of operating parameters on the performance of a biosand filter: A statistical experiment design approach. Water Sci. Technol. Water Supply 16, 775–782.

Weber-Shirk, M.L., Dick, R.I., 1997b. Biological mechanisms in slow sand filters. J. Am. Water Works Assoc. 89.

Wotton, R.S. 2002. Water purification using sand. Hydrobiologia 469: 193-201.

Wotton, R. S. & K. HirabayashI, 1999. Midge larvae (Diptera: Chironomidae) as engineers in slow sand filter beds. Wat. Res. 33: 1509–1515.

Zhuang, J., Jin, Y., 2003. Virus retention and transport through Al-oxide coated sand columns: effects of ionic strength and composition. J. Contam. Hydrol. 60, 193–209.