

1 **Rainwater treatment system efficiency: household slow sand filter combined with**
2 **UVC lamp disinfection**

3
4 **Short Title:** Rainwater treatment system efficiency

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14
15 **Abstract**

16 A household system to treat rainwater composed of a Household Slow Sand Filter (HSSF)
17 and a commercial ultraviolet lamp reactor was evaluated. Rainwater was collected in the
18 southeast of Brazil (São Carlos, São Paulo) and inoculated with *Escherichia coli* to
19 simulate contamination. The system was evaluated for 100 consecutive days under real-
20 scale conditions, aiming to remove microbiological and physical-chemical parameters.
21 Results indicated that HSSF removed 1.10 ± 0.33 log of *E. coli* even with the *schmutzdecke*
22 in slow formation due to the low concentration of organic matter concentration and
23 scarcity and low diversity of microorganisms in the rainwater. On the other hand, the UV
24 disinfection (UV dose of 30 mJ/cm²) presented an average removal of 4.60 ± 0.58 log,
25 with 87.5% of the samples presenting absence of microbiological risk. No significant
26 improvement in physical-chemical water quality after the household treatment was

27 observed due to the high quality of raw rainwater. Therefore, it was recognised that
28 rainwater quality was not substantially improved by the HSSF (i.e., filtration could be
29 dispensed) and only UVC lamp disinfection would be enough to produce drinking water.
30 Recontamination was observed during the tests, as weather events and monitored
31 parameters were capable of highlighting the importance of safe storage practices.

32

33 **Keywords:** water treatment, rainwater, biosand filter, UV disinfection, safe storage.

34

35 **1. Introduction**

36

37 Achieving universal and equitable access to safe drinking water, hygiene, and
38 sanitation is one of the Sustainable Development Goals in The United Nations Agenda.
39 Globally, almost 1.1 billion people consume water with faecal material [1,2], and more
40 than 800 thousand people die each year from diarrhoea complications resulting from
41 infections acquired from contaminated water consumption, including almost 500
42 thousand children under 5 years old [3,4,5].

43 This precarious situation is highlighted in vulnerable communities, such as rural
44 areas and low- and middle-income countries, considering they may have access to limited
45 sanitation services and water from polluted or unimproved sources [5]. In this context,
46 rainwater has been considered a potential drinking water source, mostly in rural semiarid
47 regions and isolated communities, where piped water cannot reach and access to other
48 sources is difficult. An example is the Brazilian northeast, in the caatinga biome, where
49 almost 14% of the population uses rainwater as a source of supply [6].

50 This source has been widely used for non-drinking purposes, such as gardening
51 and sanitary uses, in several countries [7,8] but its use for consumption purposes has been

52 explored and associated with appropriate treatments [9,10,11]. This is especially due to
53 its high microbiological and physiochemical quality when compared to other sources,
54 despite atmospheric pollution [12,13,14], and the concerns about leaching and weathering
55 of roof materials [15,16,17,18].

56 Overall, rainwater quality lead to better conditions for safe storage [19,20];
57 however, inappropriate practices (e.g., open tanks and easy access for animals) and
58 climate conditions can promote massive microbiological recontamination. Alim et al. [21]
59 and Chubaka et al. [22] presented an overview of roof-harvested rainwater quality in
60 storage tanks in Australia, showing the presence of *Legionella* spp., *Salmonella* spp.,
61 *Pseudomonas* spp., *Campylobacter* spp., *C. perfringens*, and Enterococci in
62 concentrations above WHO standards [2], in addition to *E. coli* concentrations ranging
63 from 17 CFU/100mL to a peak of almost 10^4 CFU/100mL, which was reported by
64 Chapman et al. [23] in Canberra.

65 Other countries have presented similar results on microbiological contamination
66 in rainwater storage tanks or harvesting systems. Islam et al. [24] noted increases in *E.*
67 *coli* concentrations after three months of storage in rainwater tanks for potable uses in
68 Bangladesh. Despins et al. [25] detected coliform presence in rainwater harvesting
69 systems in Ontario, Canada, with peaks of 400 CFU/100mL. Vialle et al. [26] monitored
70 a private house's harvesting system for one year in Southwest France, detecting
71 concentrations over 10,000 CFU/100mL for total coliforms and 5,500 CFU/100mL for
72 *E. coli*. Mazurkiewicz et al. [27] noted one of the highest bacterial loads in the literature,
73 from 10^4 to 10^6 CFU/100mL in underground rainwater storage tanks. These loads
74 occurred mainly in the summer, which is a season with better conditions for survival and
75 bacterial growth, and therefore, greater contamination. Some of these studies also related

76 the inappropriate management practices and presence of animals as possible causes of
77 contamination.

78 Some rainwater treatment strategies may include metal and chemical additives
79 [28], filtration [29], chlorination [10] ozone [30], UV radiation [31], SODIS [32], and
80 solar pasteurization [33]. Moreover, the literature has demonstrated that rainwater quality
81 still requires two treatment barriers, i.e., a step before the disinfection process [34,35],
82 which could be a simple sedimentation or a slow sand filter.

83 In rural and isolated communities, these rainwater treatment technologies must be
84 small-scale and guarantee user autonomy, besides the cheap construction cost and easy
85 installation, operation, and maintenance. However, there has been limited research
86 focused on these vulnerable scenarios [35].

87 The Household Slow Sand Filter (HSSF) is a consolidated decentralized
88 technology, whose application and efficiency have been indicated by several studies [36].
89 The HSSF can be operated in continuous or intermittent flow. Its treatment process
90 involves the removal of physicochemical parameters by filtration and adsorption
91 mechanisms in the filter sand media, and partial removal of the microbiological risk in
92 the *schmutzdecke* layer formed at the bed top [37, 38].

93 Although HSSF can remove turbidity, organic matter, and chemical compounds,
94 besides algae, bacteria, protozoa and viruses [36,39,40,41], its microbiological removal
95 can be limited, making the addition of a disinfection step essential in the treatment
96 process.

97 Ultraviolet (UV) light for water disinfection is an alternative to chlorination as it
98 does not impart smell or taste to the water and does not generate toxic by-products such
99 as trihalomethanes. Its use has been well documented by several studies using different
100 devices [41,42,43,44], the most common being the low-pressure UV-C lamps (254 nm).

101 One of the main concerns about UV disinfection is the cell repair mechanisms resulting
102 from the evolutionary processes, present even in simple organisms such as *Escherichia*
103 *coli*: photoreactivation and dark recovery phenomena. Both mechanisms must be taken
104 into consideration in UV disinfection applications [45,46,47].

105 As HSSF and UV disinfection are two efficient and well-documented treatment
106 units, there is a potential to test both as a full-scale system to treat rainwater as a drinking
107 water source. Given this scenario, our paper proposed a household water treatment system
108 composed of an HSSF operated in an intermittent flow and a commercial UVC-reactor as
109 post-treatment. In addition to providing results on system efficiency for 100 consecutive
110 days to treat harvested rainwater stored for almost 1 year, our paper highlighted points
111 about bacteria regrowth phenomena and safe storage practices.

112

113 **2. Material and methods**

114

115 **2.1. Rainwater harvesting, storage, and characterization**

116 Rainwater was harvested in São Carlos (Brazil) from November 2019 to January
117 2020 and used as influent water to the household system in April 2021. The storage of
118 water in a period prior to the development of the experiment reproduced the reality of
119 users who live in regions with intermittent rain and need to store rainwater for a long time
120 to use it for domestic and consumption purposes. The harvesting system consisted of an
121 asbestos roof, a gutter and vertical PVC pipes with an outlet to discard the first rainwater
122 and eliminate raw roof material. Subsequently, the rainwater was conducted to a 3000 L
123 reservoir in which a screen was installed to retain the leaves and sediments dragged from
124 the roof. After that, rainwater was pumped to a 15000 L storage reservoir. Three 500 mL
125 samples were collected from the reservoir in April 2021 and respectively, submitted to

126 specific physicochemical, microbiological, and metal analyses, on a spot basis, for each
 127 parameter. The main objective was to evaluate rainwater quality after storage time
 128 considering possible leaching and weathering of roof materials. All analyses followed the
 129 Standard Methods, described in Table 1 [48].

130

131 **Table 1:** Parameters and methodology applied for rainwater quality characterisation.

Parameter	Methodology/Equipment
pH	pH meter DM20 (Digimed, Brazil)
Turbidity	Turbidimeter 2100N (Hach, USA)
Apparent colour	Colorimeter DM-COR (Digimed, Brazil)
True colour	Colorimeter DM-COR (Digimed, Brazil)
Absorbance at 254 nm ^a	Nanocolor spectrophotometer (MN, Germany)
Transmittance at 254 nm ^b	Nanocolor spectrophotometer (MN, Germany)
Aluminium	SMWW 3111 D [42]
Iron	SMWW 3111 B [42]
Magnesium	SMWW 3111 B [42]
Sodium	SMWW 3500-Na B [42]
Zinc	SMWW 3111 B [42]
Calcium	SMWW 3111 D [42]
<i>Escherichia coli</i> and total coliforms	Membrane filtration [42]
Notes: ^{a, b} were measured without the 0.45 µm membrane filtration step.	

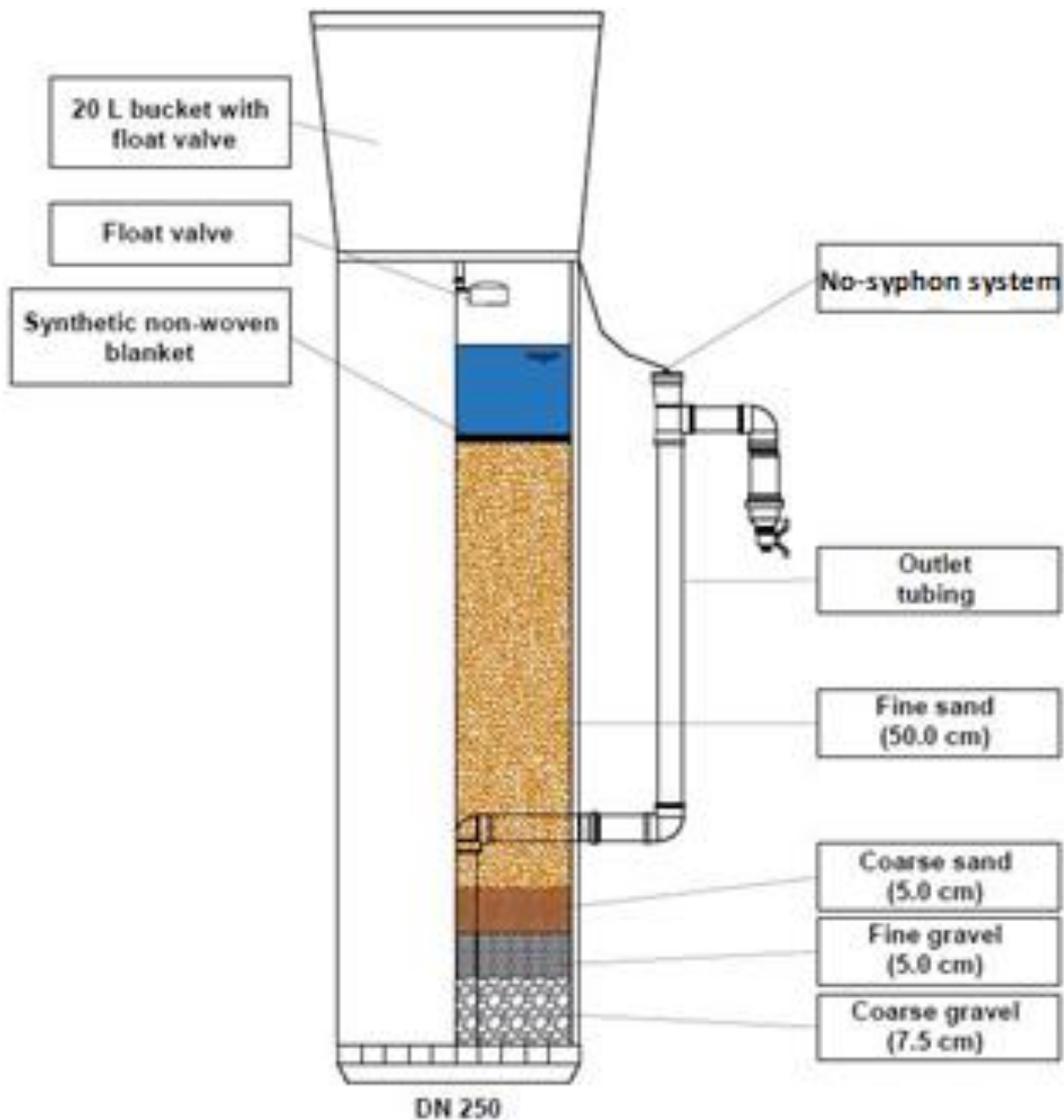
132

133 **2.2. HSSF construction**

134

135 The HSSF was constructed using PVC fittings and pipes (cross-section area of
136 0.053 m²) and a 20 L bucket with a float valve, based on Andreoli and Sabogal-Paz [39]
137 prototype model. The float was used to control the water level above the filtration layer
138 and the maximum filtration rate (MFR) [40]. MFR was measured daily considering the
139 volumetric flow after 20 minutes of feeding and the cross-section area.

140 The HSSF was filled with four granular materials: 7.5 cm of coarse gravel (7 – 12
141 mm), 5 cm of fine gravel (5 – 7 mm), 5 cm of coarse sand (0.17 – 0.67 mm), and 50 cm
142 of fine sand (effective size of 0.17 mm and uniformity coefficient of 2.27). Clean well
143 water was added to the filter before media introduction to avoid the formation of air
144 pockets. A non-woven synthetic fabric made of polyester was positioned at the filter
145 media top and fixed by a PVC ring to improve HSSF efficiency and facilitate maintenance
146 activities [36]. A schematic of HSSF is shown in Fig. 1.



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Fig. 1: Intermittent household slow sand filter (adapted from [33]).

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150 2.3. Operational settings

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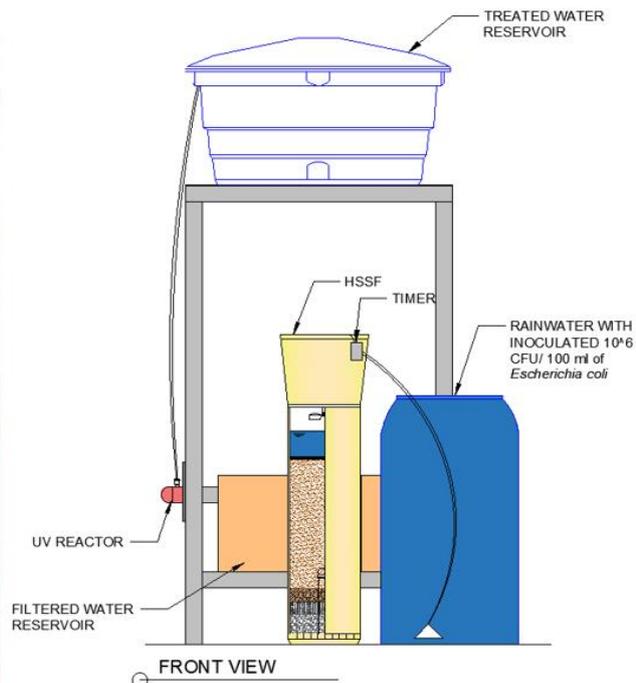
On alternate days, 120 L from the rainwater reservoir was gravity-transported to an intermediary reservoir (Figure 2 – A). As the raw rainwater had a low level of natural microbiological load (i.e., 143 CFU.100ml⁻¹), 10⁵ CFU.100ml⁻¹ of *E. coli* strains were inoculated daily in this reservoir, totalling 10⁶ CFU.100ml⁻¹, to simulate the highest

156 reservoir contamination observed in the field by Mazurkiewicz et al. [27], this also
157 enabled us to study the HSSF behaviour operating with a higher bacterial load.

158 The intermittent HSSF (Figure 2 – B) was fed three times a day, 16 L each
159 (determined by the filter media data obtained at the construction stage) every 8 hours, by
160 a pump connected to a timer. The 48 L of filtered water produced daily was stored in a
161 60 L reservoir (Figure 2 – C). The time after the water stops flowing and before a new
162 water addition, called idle time or pause period, was of 5 h and 40 min, that is, 8 h minus
163 2 h and 20 min – time for the passage of 16 L batch in HSSF. This idle time was between
164 one and 48 h, which is recommended to allow the processes to act for bacteria removal
165 [49]. After feeding the HSSF for two days, the remaining water in the intermediary
166 reservoir (about 20 L) was discharged before receiving new water on the next day.

167 Prior to disinfection, the UV-C reactor (Figure 2 – D) was powered on 10 min for
168 heating the lamp and then 48 L of filtered water were pumped into the reactor. The flow
169 rate for disinfection was 2 L.min⁻¹ (equivalent to an UV dose of 30 mJ/cm²), which is the
170 rate recommended by the fabricant for a 10⁴ CFU.100mL⁻¹ *E. coli* removal. The
171 disinfected water was stored in a 150 L elevated reservoir (Figure 2 – E).

172 The household water treatment system was operated for 100 consecutive days.
173 After the operation, disinfected water was maintained for 15 consecutive days to regrowth
174 analyses of *E. coli* and safe storage tests by monitoring turbidity, colour, and
175 microbiological parameters. A photo and a schematic of the system are shown in Fig. 2.



176

177 **Fig 2:** Left: Photo of the system. Right: Schematic of the household water treatment
 178 system.

179

180 **2.4. Regrowth, recontamination and safe storage tests**

181

182 After the household water treatment system operation, the disinfected water
 183 volume of the last day (48L) was equally divided and conducted to two different
 184 reservoirs (apart from the one shown in Fig. 2). The first one was completely sealed and
 185 the second one was covered only with a screen to avoid vectors and small animals. During
 186 the 15 consecutive days, samples from the two reservoirs were submitted to turbidity,
 187 apparent colour, *E. coli*, and total coliforms analyses, to evaluate the occurrence of
 188 regrowth phenomena or contamination from the external environment by particles.

189

190 **2.5. Sample collection, physicochemical and microbiological analyses**

191

192 Raw rainwater (RRW), filtered rainwater (FRW), and disinfected rainwater
 193 (DRW) were collected daily. RRW was collected from the intermediary reservoir (Figure
 194 2 – A), FRW was collected from the 60 L filtered water reservoir (Figure 2 – C), and
 195 DRW was collected from the elevated 150 L reservoir (Figure 2 – E). Parameters,
 196 frequencies, and methodology applied are presented in Table 2. All the parameters were
 197 evaluated following Standard Methods [48].

198

199 **Table 2:** Parameters, frequency, and methodology applied for water quality measurement

Parameter	Frequency	Methodology/Equipment
Temperature	Daily ^c	Mercury thermometer
Turbidity	Daily	Turbidimeter 2100N (Hach, USA)
Apparent colour	Daily	Colorimeter DM-COR (Digimed, Brazil)
True colour	Weekly ^c	Colorimeter DM-COR (Digimed, Brazil)
Alkalinity	Weekly	Standard Method 2320 [42]
pH	Daily	pH meter DM20 (Digimed, Brazil)
Conductivity	Daily	Conductivity meter DM32 (Digimed, Brazil)
Absorbance at 254 nm ^a	Daily	Nanocolor spectrophotometer (MN, Germany)
Transmittance at 254 nm ^b	Daily	Nanocolor spectrophotometer (MN, Germany)
Nitrate	Weekly	DR5000 spectrophotometer (Hach, USA)
Nitrite	Weekly	DR5000 spectrophotometer (Hach, USA)
Silica	Weekly	Nanocolor spectrophotometer (MN, Germany)

Particle size distribution	Weekly	Zetameter Zetasizer Nano Series ZS90 (Malvern Panalytical, UK)
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<i>Escherichia coli</i> and total coliforms	2x a week	Membrane filtration [48].
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Notes: ^{a, b} were measured without the 0.45 µm membrane filtration step. ^c Daily and weekly analyses were not performed on weekends or holidays.

200

201 Other operational parameters, such as the room temperature and HSSF flow rate
202 were measured to evaluate their interference with the treatment process. Significant
203 reductions in flow rates were an indicative that the HSSF needed cleaning processes.

204 At the end of the operation, *schmutzdecke* samples from the non-woven blanket
205 and the first 5 cm of sand were collected and analysed for solids, according to Standard
206 Methods [48]. These samples were also concentrated by triple centrifugation (1000×g)
207 and a drop of the concentrated sample was used for morphological identification of
208 organisms by bright field microscopy (Olympus ® BX60, Japan) at 10x to 800x
209 magnification.

210

211 **2.6. Statistical analyses**

212

213 All statistical analyses were executed on PAST 3.25 software (PAlaeontological
214 Statistics). The obtained datasets were submitted to Shapiro-Wilk test to evaluate the
215 normal distribution. Considering all obtained datasets as dependent data, normal
216 distribution datasets were compared by Student's t-test paired and non-normal datasets
217 were compared by Wilcoxon test. All tests were performed on pairwise and considering
218 a significance level of 5% ($p < 0.05$).

219 Bivariate analyses were performed to correlate system's performance parameters
220 and operating parameters (operating time, turbidity of raw water and flow rate) by
221 Spearman's correlation test. A significant correlation was defined as having both $p < 0.05$
222 and $|r|$ greater than r -critical.

223

224 **2.7. System financial investment**

225

226 After the experimental stage, all items for building the household system have
227 been listed and economically quoted taxes values were updated to the current year of 2023
228 in Brazil and the final amount was converted to US dollars. A list of items and respective
229 values are available on Table S1 – Supplementary Material.

230

231 **3. Results and Discussion**

232

233 **3.1. Rainwater characterisation**

234

235 Rainwater was analysed on a spot basis and compared to the WHO Guidelines to
236 drinking water values for water quality [2]. The data summary of each parameter
237 evaluated is shown in Table 3.

238

239 **Table 3:** Rainwater characterisation parameters, determined values and limit values of
240 WHO.

Parameters		Value	Limit [2]
Physicochemical	pH	6.72	6.5 – 8.5
	Turbidity (NTU)	1.13	< 5.0 (Ideally < 1.0) ^c

	Apparent colour (mg Pt-Co/L)	15.20	-
	True colour (mg Pt-Co/L)	6.00	15.0
	Absorbance at 254 nm ^a (cm ⁻¹)	0.088	-
	Transmittance at 254 nm ^a (%)	79.2	-
	Aluminium (mg/L)	ND ^b	< 0.9
	Iron (mg/L)	ND ^b	< 0.2
	Magnesium (mg/L)	0.59	-
	Zinc (mg/L)	0.49	< 3.0
	Sodium (mg/L)	2.30	< 200.0
	Calcium (mg/L)	14.44	< 300.0
Microbiological	<i>E. coli</i> (CFU/100mL)	143	0
	Total coliforms (CFU/100mL)	ND ^b	0

Notes: ^a Absorbance at 254 nm and Transmittance at 254 nm were measured without the 0.45 µm membrane filtration step; ^b not detected; ^c the limit value in more restrictive countries, such as Brazil for example [50].

241

242 All parameters except *E. coli* were in accordance with WHO recommendations,
 243 reinforcing that rainwater could be a promising source of drinking water [8,13]. The
 244 concentration levels of aluminium, iron, magnesium, zinc, sodium, and calcium were
 245 below the limit recommended by WHO, therefore physicochemical contamination by
 246 leaching or weathering of roof material was discarded, as well as their monitoring
 247 throughout the operation. Turbidity concentration was in accordance with the WHO
 248 limits, but its value was above the ideal in more restrictive countries such as Brazil [44].

249

250 **3.2. HSSF filtration rate and operational parameters**

251

252 The system was operated during all the winter and the beginning of spring, the dry
253 season in Brazil. During this operation period, the average ambient temperature was 19.5
254 $\pm 4.8^{\circ}\text{C}$ and the average temperature for filtered water samples was $17.8 \pm 4.0^{\circ}\text{C}$. The
255 lower temperatures after the HSSF (Wilcoxon test, $p < 0.001$) proved that the PVC in its
256 body has thermic isolation properties for drinking water.

257 The intermittent HSSF had an average MFR of $9.83 \text{ m}^3/\text{m}^2.\text{day}$ (interval between
258 8.69 and $11.41 \text{ m}^3/\text{m}^2.\text{day}$). This value was higher than other studies with HSSF treating
259 different influent water qualities, especially those HSSF aimed at treating water with a
260 large amount of particles, such as surface water [34,35]. The concentration of suspended
261 material in the rainwater was not high enough to obstruct the intergranular voids, increase
262 the head loss and reduce the MFR in the filter runs. As MFR did not decline, maintenance
263 activity was dismissed during the operation time.

264 Despite the results not indicating how long the HSSF could operate without
265 maintenance, as the experiment was made for 100 days only, there is a hypothesis that
266 the filter could still treat a larger volume of rainwater until reaching its saturation point.
267 Andreoli and Sabogal-Paz [39] pointed out that intermittent HSSF is capable of treating
268 water with a small amount of particles for more than 200 days without requiring any
269 maintenance activity. Further studies should analyse HSSF under long-term operations
270 for rainwater treatment.

271

272 **3.3. HSSF performance**

273

274 The HSSF was evaluated by its removal efficiency of each parameter and posterior
275 comparison to reference values (Table 4).

277 **Table 4:** Filtration results for each parameter and its removal efficiency percentage.

Parameters	Number of samples	Mean \pm SD ^a		% of Removal (R) or variation (V) \pm SD ^a	p-value
		RRW	FRW		
pH	67	7.05 \pm 0.07	7.15 \pm 0.08	1.48 \pm 0.83 (V)	< 0.001
Conductivity (μS/cm)	67	49.62 \pm 7.23	49.69 \pm 4.35	0.15 \pm 9.91 (V)	0.94
Turbidity (NTU)	67	0.31 \pm 0.07	0.40 \pm 0.12	30.29 \pm 32.54 (V)	< 0.001
Apparent colour (mg Pt-Co/L)	67	9.30 \pm 1.34	7.12 \pm 1.17	23.46 \pm 12.84 (R)	< 0.001
True colour (mg Pt- Co/L)	15	7.44 \pm 1.04	5.54 \pm 1.27	25.54 \pm 12.63 (R)	< 0.001
Absorbance at 254 nm (cm⁻¹) ^b	67	0.053 \pm 0.005	0.044 \pm 0.007	16.11 \pm 13.63 (V)	< 0.001
Transmittance at 254 nm (%) ^b	67	88.49 \pm 0.77	90.24 \pm 1.31	1.98 \pm 1.96 (V)	< 0.001
Partial alkalinity (mgCaCO₃/L)	15	16.62 \pm 0.47	16.83 \pm 0.44	1.23 \pm 1.79 (V)	0.15
Total alkalinity (mgCaCO₃/L)	15	23.12 \pm 0.59	23.37 \pm 0.57	1.10 \pm 1.44 (V)	0.07

Nitrite (mg/L)	15	0.021 ± 0.003	0.021 ± 0.006	0.00 ± 14.57 (R)	0.96
Nitrate (mg/L)	15	1.65 ± 0.58	1.63 ± 0.46	1.21 ± 16.08 (R)	0.80
Silica (mg/L)	15	1.46 ± 0.06	1.58 ± 0.31	8.41 ± 21.65 (R)	0.05
Particle Size (nm)	15	1820 ± 453	1301 ± 263	28.52 ± 19.42 (V)	< 0.001
Total coliforms (CFU/100mL)	28	Absence	Absence	NA	NA
<i>E. coli</i> (CFU/100mL) ^c	28	6.38E+05 ± 9.50E+05	4.50E+04 ± 5.04E+04	92.95 ± 9.38 (1.10 ± 0.33 log) (R)	< 0.001

Notes: ^a Standard deviation, ^b Absorbance at 254 nm and Transmittance at 254 nm were measured without the 0.45 µm membrane filtration step. NA – not applicable, ^c *E. coli* results were calculated using geometric means, while arithmetic means were used for the remaining parameters.

278

279 It is important to highlight that the rainwater originally presented high physical-
280 chemical and microbiological quality. Therefore, to evaluate the HSSF and, mostly, the
281 UV reactor performances, a high concentration of strains of *E. coli* was inoculated. For
282 this reason, all parameters except for *E. coli* were according to WHO Guidelines for
283 drinking water limits.

284 The following parameters presented significant statistical differences ($p < 0.05$)
285 between raw and filtered rainwater: pH, turbidity, apparent colour, true colour,

286 absorbance and transmittance at 254 nm, silica, particle size and *E. coli*, which means the
287 HSSF affected filtered water quality. Turbidity, pH, transmittance at 254 nm and silica
288 values increased after the HSSF, while apparent colour, true colour, absorbance at 254
289 nm, particle size, and *E. coli* values reduced.

290 Spearman's bivariate analyses (Table S2 – Supplementary Material) pointed out
291 a strong and positive correlation ($p < 0.05$) between FRW turbidity and RRW turbidity,
292 showing that increases in influent water turbidity influenced the filtered water.
293 Furthermore, there was a strong correlation between pH, absorbance and transmittance at
294 254 nm of filtered water with all operational parameters (operation time, RRW turbidity
295 and flow rate).

296 Despite the significant statistical difference in both univariate and bivariate
297 analyses, the HSSF is not the usual technology recommended for this type of influent
298 water with high physical-chemical quality. However, our study chose to maintain the
299 filtering barrier to check if the microbiological process within HSSF could improve the
300 system efficiency removal, mainly in scenarios of high biological contamination as
301 simulated.

302

303 **3.3.1. Turbidity**

304

305 The average turbidity values of RRW and FRW were respectively 0.31 ± 0.07
306 NTU and 0.40 ± 0.12 NTU (Table 4), all below the reference for drinking water [2].

307 HSSF usually removes turbidity between 60-99% [51,52,53], but low removals
308 (i.e. $\leq 50\%$) are also expected when the influent water has low turbidity (e.g. preserved
309 groundwater and pre-treated water) [39,54,55,56]. Nevertheless, our HSSF did not
310 remove turbidity but increased the turbidity of the filtered water samples ($p < 0.001$).

311 Two possible reasons for this increase in turbidity are: (A) The sensitivity of
312 rainwater to contamination effects by particles, since this matrix already presented low
313 turbidity, so any suspended particles that could enter the system through small orifices or
314 being resuspended by pumping could affect its quality. (B) The leaching of the HSSF
315 filter media treating water with good physical-chemical quality [57, 58].

316 Besides a small increase in filtered samples in comparison to raw samples, we also
317 noted a decrease in raw samples' turbidity when compared to those collected at the
318 characterisation step (Table 3), from 1.13 NTU to 0.559 NTU. The first sample was
319 collected from an outlet tube at the bottom of the 15000 L reservoir where the rainwater
320 was stored for almost one year; therefore, this sample had more particles resulting in
321 higher turbidity.

322 The second sample, on the other hand, was collected from the intermediary
323 reservoir, after being transported by gravity from the 15000L reservoir to begin the
324 operation, presenting a lower turbidity level. This occurrence highlights the effects of
325 decantation process on the suspended particles in stored water and encourages further
326 research for solutions that avoid this transport of decanted particles, especially in field
327 applications.

328

329 **3.3.2. Silica**

330 The mean concentration for silica was 1.46 ± 0.06 mg/L in the RRW samples and
331 1.58 ± 0.31 mg/L in FRW samples. In the first two weeks of operation, silica
332 concentration in filtered samples was even higher, with values of 2.64 mg/L and 1.82
333 mg/L in the first and second weeks, respectively. Silica was monitored to verify for
334 leaching from the filter media, as its presence in higher doses may pose a health risk in
335 terms of drinking water. The significant statistical difference between the raw and filtered

336 samples ($p = 0.05$) provides further indication that the filter media actually did leach, at
337 least in the first weeks. Sabogal-Paz et al. [58] also observed this phenomenon in
338 intermittent HSSF treating water with a low concentration of mineral ions.

339

340 **3.3.3. Organic matter**

341

342 Organic matter (OM) on water samples can be inferred by true colour and
343 absorbance at 254 nm values. For both parameters, the removal percentage was 25.54%
344 for true colour and 16.11% for absorbance, similar values to those presented by the
345 literature that do not exceed 30% of removal [36]. This percentage implies that HSSF has
346 limited capacity to remove OM, especially on a cleaner matrix as rainwater, which was
347 expected.

348

349 **3.3.4. Other physicochemical parameters**

350

351 In general, pH presented a mean value of 7.05 ± 0.07 for RRW samples and 7.15
352 ± 0.08 for FRW samples. A hypothesis is that this small increase is related to the ions
353 coming from the leached filter media [58]. The pH values did not exceed the
354 recommendations of WHO [2] in any of the samples. Spearman's bivariate analyses
355 showed a strong correlation between pH and all the operational parameters ($p < 0.001$),
356 which means that operation time, flow rate and RRW turbidity were capable of
357 influencing pH values. A negative correlation between operation time and pH showed
358 that pH was reduced if the operation time increased, which is consistent with the reduction
359 of the leaching phenomenon after a few weeks observed in silica analyses.

360 The average values for particle size distribution were 1820 ± 453 nm in the raw
361 samples and 1301 ± 263 nm in the filtered samples, which showed a significant statistical
362 difference ($p < 0.001$) and a reduction in the average diameter of the grains of 28.52%.
363 This demonstrates that there were physicochemical and microbiological retentions in the
364 intergranular voids of the filter media.

365 Terin et al. [40] and Medeiros et al. [55] also indicated this diameter size reduction
366 using HSSF to treat simulated groundwater and surface water, but the average size values
367 for the grains present in those types of influent water were lower than those in rainwater.
368 It is also important to highlight that particle retention can reduce or improve HSSF
369 efficiency. Fulfillment of the intergranular voids can obstruct the filter media, increasing
370 the head loss and reducing the MFR, otherwise, this retention can contain microorganisms
371 that will contribute to biolayer formation and maintenance [59].

372 Despite that, there was no evidence or correlation indicating that this particle
373 retention could reduce or improve HSSF efficiency. The retention phenomenon can also
374 be observed in the increase in transmittance values in the filtered water samples.

375 Nitrogen compounds are related to water pollution and eutrophication, but nitrite
376 and nitrate values were not worthy of concern during operation. The limits established by
377 WHO recommendations for these parameters are 3.0 mg/L and 50.0 mg/L, respectively.
378 The mean values for nitrite and nitrate in filtered rainwater were 0.021 ± 0.006 mg/L and
379 1.63 ± 0.46 mg/L, respectively. There was no significant statistical difference between
380 the samples.

381

382 **3.3.5. *E. coli* removal**

383

384 Total coliforms and *E. coli* were quantified twice a week during operation, but
385 total coliforms were not detected in any of the samples. The mean removal value of *E.*
386 *coli* by the intermittent HSSF was 1.10 ± 0.33 log, a low value compared to other
387 references using HSSF to treat consumption water [36].

388 One possible reason for the low removal value is related to the MFR because it
389 reduces the period of pause to microbiological mechanisms within HSSF [40]. The other
390 four reasons are related to the matrix quality in comparison to other matrices. (A) The
391 low concentration of solids in the influent water reduced the retention by the filtration
392 mechanism, considering that removal levels are higher when influent levels are higher
393 [57]. (B) *schmutzdecke* still in formation, which is primordial in microorganisms'
394 retention [60]. (C) operation time as the literature indicates that the *schmutzdecke* takes
395 almost 30 days to form and it may take longer due to several external factors [61].
396 Although this study was carried out for a much longer time than indicated in the literature,
397 the filter did not reach its full efficiency, indicating that not all matrices fit this timing
398 rule, which was also observed by Andreoli and Sabogal-Paz [39] and by Lubarsky et al.
399 [59] treating groundwater at one of the research stages. Finally, (D) the low nutrient
400 concentrations in the raw rainwater compared to other types of influent water from similar
401 studies [53] did not favour the biological layer formation [59].

402

403 **3.4. UV disinfection performance**

404

405 The UV reactor disinfection was evaluated according to its efficiency on removing
406 microbiological risk until the complete absence in the water samples, which is
407 recommended by World Health Organization. After previous tests, the fabricant
408 recommended dose of 30 mJ/cm^2 presented a satisfactory value with 4.28 ± 0.25 log of

409 inactivation, confirming that this dose is also correct for this type of matrix, and lower
410 doses could be sublethal to the bacteria community, leading to regrowth phenomena.

411 Among the 25 samples analysed during the operation, 87.5% presented a complete
412 absence of *E. coli* after UV disinfection and 12.5% presented concentration values lower
413 than 5 CFU/100mL, which is classified as low-risk water [2]. The remaining bacteria
414 could be associated with limitations of the UV disinfection system due to the presence of
415 a high concentration of *E. coli*. Suspended solids could also interfere with disinfection
416 efficiency, however residual turbidity, colour, absorbance, and transmittance values did
417 not corroborate with this possibility once there was no statistical correlation indicating
418 this occurrence.

419 Despite that, UV inactivated a mean value of 4.60 ± 0.58 log of *E. coli* during
420 operation. This value was higher than those obtained by Garcia et al. [41] because our
421 matrix was excessively contaminated by faecal bacteria, which is not a recurrent situation
422 in environmental matrices. Even in our simulated scenario, the UV disinfection was
423 capable of producing drinking water with improved quality and in most treated samples,
424 there is no risk of water consumption by bacteria (i.e., absence of *E. coli*).

425

426 **3.5. Recontamination and safe storage tests**

427

428 Organisms' regrowth possibility due to photoreactivation or dark recovery
429 phenomena and external recontamination were considered, however the environmental
430 conditions did not allow to safely affirm the occurrence of regrowth phenomena. To
431 verify the external contamination possibility, *E. coli* and total coliform parameters were
432 monitored in two reservoirs. The first one completely sealed and the second one, non-
433 covered with just a screen. Each reservoir had a volume of approximately 24 L of

434 disinfected water. Results for *E. coli* and total coliforms are respectively in Fig. S1 and
435 Fig. S2 in Supplementary Material. The disinfected water sample on Day 0 presented a
436 complete absence of *E. coli* or coliforms.

437 Both parameters presented a significant statistical difference between reservoirs
438 ($p < 0.001$). The non-covered reservoir always showed higher concentration values of *E.*
439 *coli* and coliforms than the covered reservoir, with peaks of 470 CFU/100mL and 70
440 CFU/100mL, respectively. As the concentration values for microbiological parameters in
441 the covered reservoir were null or low on the observed days, external contamination was
442 considered responsible for the increased microbiological risk in a non-covered reservoir,
443 however regrowth possibility could not be confirmed or refuted.

444 Testing the possibility of recontamination, turbidity and apparent colour was also
445 monitored to verify the occurrence of external physicochemical contamination by
446 suspended solids. On day 0, the disinfected water sample in covered and uncovered
447 reservoirs presented turbidity values of 0.357 and 0.363 NTU, and apparent colour values
448 of 8.2 and 8.4 mg Pt-Co/mL, respectively.

449 Again, during the regrowth period, all the concentration values were higher in the
450 non-covered reservoir ($p < 0.001$). Mean turbidity and apparent colour in the non-covered
451 reservoir was 2.06 NTU and 9.4 mg Pt-Co/mL, with peaks of 9.39 NTU and 14.6 mg Pt-
452 Co/mL. On the other hand, in the covered reservoir, the average values of turbidity and
453 apparent colour were 0.325 NTU and 7.8 mg Pt-Co/mL.

454 The peaks of all parameters in the non-covered reservoir, including *E. coli* and
455 coliforms, coincided with a dust cloud that affected São Carlos with winds up to 92 km/h
456 on October 3rd and 4th of 2021 (days 10 and 11 of regrowth tests). These results showed
457 an occurrence of external contamination and the relevance of treated water safe practices
458 of storage and maintenance.

459

460 **3.6. *Schmutzdecke* evaluation**

461 At the end of the operation, the *schmutzdecke* was evaluated based on total and
462 suspended solids analyses, in addition to microscopy investigation for morphological
463 identification of the organisms present in this biological layer.

464 Both total and suspended solids analyses (Table S3 – Supplementary material)
465 revealed higher concentrations of volatile solids, directly correlated to a predominance of
466 organic matter. The concentration of volatile total solids in the sand and the non-woven
467 blanket, positioned at the filter media top, were 0.105 mg/mL and 0.057 mg/mL,
468 respectively, representing 88% and 83% of the full sample. The concentration of volatile
469 suspended solids in the sand was 0.032 mg/mL (66% of the full sample); however, it was
470 equal to 0 mg/mL in the blanket samples.

471 Compared to studies that treated surface or groundwater and evaluated the same
472 parameters, the present one showed less significant values for total solids, as well as
473 divergence in the percentages of fixed and volatile solids. It should be mentioned that the
474 the percentage of the fixed ones stood out [41,53,55]. These phenomena were expected
475 as the rainwater was cleaner with a lower concentration of total solids than other water
476 sources, however with a higher percentage of volatile solids due to the massive
477 inoculation of *E. coli* strains.

478 Through microscopic analysis, the presence of microorganisms could be observed
479 in both the non-synthetic blanket and sand samples (Table S4 – Supplementary Material).
480 While cyanobacteria and microcrustaceans were observed in sand samples, protozoa and
481 helminths were found in blanket samples. Rotifers could be observed in samples from
482 both locations.

483 However, the results highlighted the numerical scarcity and low diversity found
484 in *schmutzdecke*, compared to other studies with HSSF [41,53,59]. This difference can be
485 attributed to the characteristics of the matrix, which, in this study, was not from a surface
486 source, and therefore was subject to less human and animal interference, nor exposed to
487 sunlight, which would favour the proliferation of algae.

488 The results provided by the microscopic investigation indicated that there was no
489 consolidated *schmutzdecke*. Two facts were considered as possible negative influences
490 on the biological layer development: (A) the system was operated for 100 days; and (B)
491 the scarcity of algae that represent, along with bacteria, one of the bases that form the
492 glycoprotein matrix through the production of polysaccharides [59]. Only in a long-term
493 operation could we infer whether the clean rainwater matrix really does not provide an
494 organic load for the biological layer development.

495

496 **3.7. Cost of the system**

497

498 The total system was quoted in February 2023 at US\$ 718.29, of which US\$ 91.55
499 are for the intermittent HSSF, US\$ 251.09 for support items such as metallic structure,
500 reservoirs, and pipes, and US\$375.65 for items of the post-treatment stage using UV
501 reactor. The harvesting system was not quoted; consequently, the total cost for the system
502 could be higher.

503 Considering the characteristics of the influent water of this research, HSSF could
504 be dismissed and this value could be reduced to just the UV reactor cost (US\$375.65).
505 Despite the cost being higher than solar disinfection solutions adopted in Ethiopia and
506 Malawi (between 200 and 300 US dollars) [62], the UV reactor is a solution that does not
507 require optimal climatic conditions for its operation.

508 People in low- and middle-income countries could have a significant amount of
509 their budget committed to this household system [62]. In some locations, a household
510 could not afford the installation cost without public economical support, but in others, the
511 cost per litre can be compatible with the minimum income and the system could be a
512 solution for an isolated facility or small community, such as Maciel et al. [63] prototype.

513

514 4. Conclusions

515

- 516 • Raw rainwater already met the physical-chemical qualities required by the WHO
517 for drinking water.
- 518 • Despite treating rainwater with low concentrations of solids and pollutants, the
519 colour, absorbance, and transmittance at 254 nm parameters showed that HSSF
520 still was able to reduce organic matter concentration on a limited scale.
- 521 • The HSSF was capable of removing an average 1.10 ± 0.33 log of *E. coli*, even
522 presenting a *schumtzdecke* still in formation and after 100 days of operation.
- 523 • The filtration results indicated that rainwater with high physicochemical quality,
524 but high microbiological contamination could dismiss HSSF, as only decantation
525 and UV disinfection would be able to reach drinking water standards
526 recommended by WHO.
- 527 • The UV disinfection was capable of removing the bacterial concentration in
528 87.5% of the samples and left remaining *E. coli* in 12.5% of the samples with a
529 concentration value lower than 5 CFU/100 mL. The average logarithmic removal
530 in UV disinfection was 4.60 ± 0.58 log.

531 • Regrowth phenomena could not be detected under the environmental conditions
532 of this research; however, external recontamination occurred, reinforced by
533 weather events, highlighting the importance of safe storage practices.

534

535 **Declaration of competing interest**

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

539

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545

546 **Supplementary material**

547 *E. coli* and total coliform regrowth tests, statistical analyses results, quotation for
548 the treatment system items and biological layer evaluation are shown in the
549 supplementary material.

550

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