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Evaluation of an alternative household water treatment system based on slow filtration and solar disinfection

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ABSTRACT

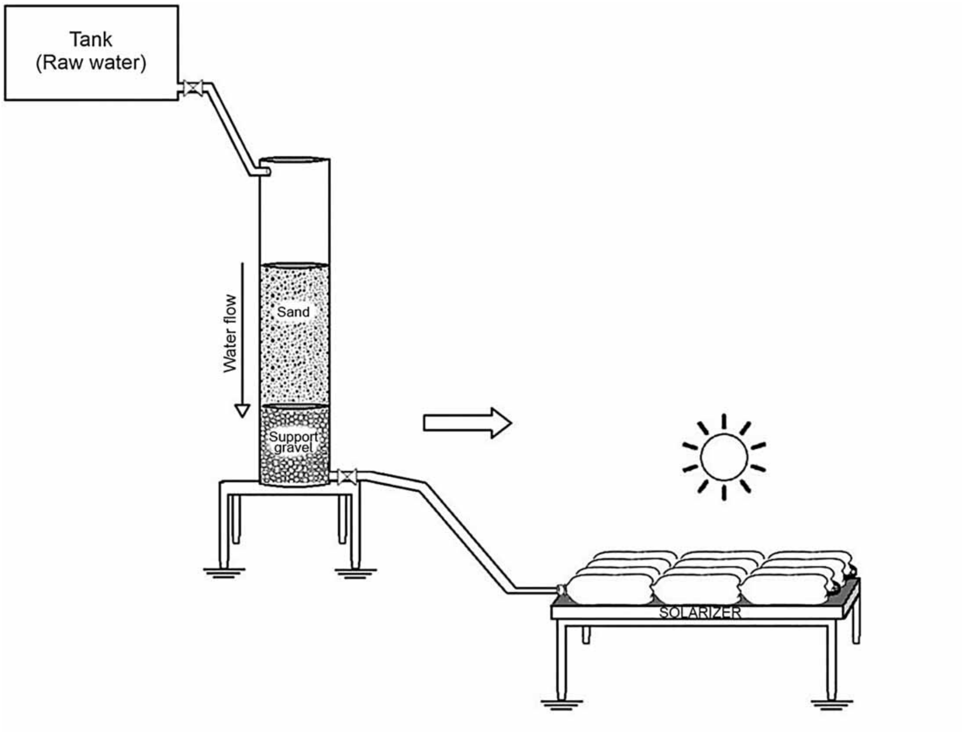
Drinking water consumption is essential to maintain a good quality of life, but it is not available for all communities. Therefore, this work aimed to develop an alternative and accessible process for water treatment, based on filtration and solar disinfection, and evaluate it in both bench and pilot scales. The construction cost of the system was estimated and compared with other available options so that its economic viability could be discussed. For this purpose, water from a stream was collected and analyzed. A filter made of PVC tubes, sand, and gravel was built, acting, respectively, as a column, filtering medium, and support layer. As for the disinfection process, the SODIS (Solar Water Disinfection) methodology was adopted. The water was exposed to the sun, and the best exposure time was determined based on the analysis of total coliforms and *E. coli*. Finally, a prototype was built for a flow rate of 37.5 L d^{-1}, consisting of two filters operating at a filtration rate of 2.38 m^3 m^{-2} d^{-1}. About 97% turbidity removal was obtained, as well as 99.9% for total coliforms and 99.1% for *E. coli*. It is estimated that the cost of building a water treatment system for one person is approximately USD 29.00.

Key words: low-cost treatment, potable water, simplified treatment, slow filtration, solar disinfection

HIGHLIGHTS

- On pilot-scale tests, slow filtration showed high efficiency on bacteria removal, which indicates that a biological layer was formed during the operation.
- The SODIS treated water should be stored at a low temperature or used as soon as possible, due to the bacteria regrowth process that can occur overnight.
- The system costs around 116 USD for a four-people house, which is considered affordable for low-income families.

GRAPHICAL ABSTRACT



1. INTRODUTION

Freshwater is essential to daily human activities and is considered necessary to maintain life on Earth. For its safe consumption by the population, the national and international standards of quality and potability for freshwater must be respected. However, data show that about 785 million people worldwide lack access to drinking water, while 144 million depend on surface water to survive (World Health Organization 2019). In Brazil, nearly 84% of the population has treated water supply, which means that 35 million people do not have access to that service (Sistema Nacional de Informações Sobre o Saneamento 2019).

In locations where there is no treated water supply by the government, household water treatment systems, that have simple operation installation, are an alternative. This system can be built with many components, such as filters made of common materials, like anthracite, pottery, and sand (Yusuf *et al.* 2017). The filters can be classified as fast or slow, which is determined by their cleaning method and the speed of water flow. The fast filtration has a filtration rate between 120 and 480 $m^3 m^{-2} d^{-1}$ and demands chemical coagulation as a pre-treatment to assure the removal of the contaminants, which makes it unviable to household water treatment systems. On the other hand, slow filtration, also known as biological filtration, which has a filtration rate between 1 and 7.5 $m^3 m^{-2} d^{-1}$, is the oldest water treatment technology, used for 200 years and still considered efficient. Many authors evaluated the use of small slow filters for water treatment and find turbidity removal efficiency higher than 80% (Young-Rojanschi & Madramootoo 2014).

Besides the high turbidity removal, slow filtration can also partially remove bacteria and viruses in water. One of the most important factors in the removal of those pathogens is the sand size. Smaller particle sizes form a compacter media that hinder the passage of part of the bacteria (Jenkins *et al.* 2011). In addition, the formation of a biological filtration media, named *Schmutzdecke*, makes the filter reach its maximum performance combining physical and biological processes, with over 99% removal of *Escherichia coli* (Matuzahroh *et al.* 2020). However, that removal is only possible when the *Schmutzedecke* is completely formed, which tends to happen only on long-term operating systems (Andreoli & Sabogal-Paz 2020). Studies indicate that the chemical, physical, and biological interactions that happen while the system is operating make the viral load removal increasingly efficient (Elliott *et al.* 2011). Therefore, on short-term systems, final disinfection of the water is necessary (Langenbach *et al.* 2010). Another extremely important point for the removal of pathogens on slow filtration is the condition of operation, causally related to the formation of *Schmutzedecke*. The continuous process tends to have a better efficiency compared to intermittent, despite that both systems show good results (Young-Rojanschi & Madramootoo 2014).

There are some disinfection methods available for household water treatment, like boiling, chlorination, flocculation, and solar disinfection, which stand out because of their simplicity and low cost. Also known as SODIS, the method, recommended by the World Health Organization (WHO), can disinfect water inserted in a transparent bottle, made of PET for example, and exposed to sunlight for between 6 and 48 h (McGuigan *et al.* 2012). Low cost, simplicity, ease to use, maintenance, and sustainability make SODIS one of the greatest options for household water treatment systems, mostly in needy communities (McGuigan *et al.* 2012). SODIS is based on the fact that most microorganisms in the water have a high vulnerability to UV radiation and heat. Thus, it is possible to inactivate bacteria commonly found in water, such as *Escherichia coli*, *Vibrio cholerae*, *Streptococcus faecalis*, *Pseudomonas aeruginosa*, *Shigella flexneri*, *Salmonella typhi*, *Salmonella enteritidis*, *Salmonella paratyphi*, and some viruses like bacteriophage, rotavirus, encephalomyocarditis virus, and *Cryptosporidium sp.* virus.

The microbial inactivation is due to both direct and indirect light absorption by chromophores. In the first case, the chromophores are always part of the microorganism (protein and nucleic acid), which absorbs higher frequency photons (UV-B), causing chemical changes in their structures, like dimerization of pyrimidines, inactivating the cell (Nelson *et al.* 2018). The indirect inactivation occurs intermediated by a chromophore which can be part of the microorganism or an external compound (dissolved organic matter, metal complexes, nitrates, nitrites). Those compounds absorb photons from UV-A and visible spectre and reach an excited state that causes the formation of highly reactive species, like singlet oxygen and hydroperoxyl radical, which prevent cell reproduction and kill microorganisms (Nelson *et al.* 2018). Also, longer wavelengths, like infrared radiation, on about 800 nm, raise the liquid temperature and can inactivate microorganisms that are sensitive to heat. This was confirmed by studies of Marques *et al.* (2013), which observed that water submitted to radiation, with peaks of 685.6 W/m^2, reached 50 °C, resulting in inactivation of 99% of *E. coli*.

The technology based on solar disinfection shows itself promising when used for the treatment of large volumes of rainwater. For raw water with 43% more *E. coli* than the drinking water standard, a period of sunlight exposure of only 8 h was enough to reduce about 75% (Reyneke *et al.* 2020). However, the storage of water treated by SODIS needs attention, once studies show that surviving microorganisms can proliferate again, as well as bacteria that suffer low damage can regrowth, especially when the water is stored in dank places (Vivar & Fuentes 2016).

Some important parameters for the good performance of household systems based on solar disinfection are the water turbidity, the depth of water, and dissolved oxygen. The turbidity is an extremely important factor in the application of SODIS, once high turbidity harms the intensity the light penetrates in water, reducing the efficiency of the process (Marques *et al.* 2013).

In this context, this article aims to propose and evaluate a simplified alternative water treatment system, composed of slow filtration, using sand as the filtration media and gravel as support, and solar disinfection. Only low-cost materials, easily found in local small construction stores, were chosen for the system, so that needy communities without access to drinking water could employ it. The cost of the system was estimated and compared with other available options. The case study was accomplished in the town of Funilândia, a small municipality in Brazil.

2. METHODS

2.1. Water sample collection

Water used in this study was collected from a stream called Pau de Cheiro, located in Funilândia, a city in the State of Minas Gerais, Brazil. This stream was chosen for this study because it was reported that people consumed its water when the pump from the local artesian well stops working, even though the local sanitation company indicates that it was not appropriate for consumption. To collect samples, previously sanitized 20 L drums were used. Samples were then kept in a 5 °C freezer for a maximum of 3 days. To determine the water collection point for treatment tests, samples of water were collected in different locations, and coliforms and *E. coli* were analyzed according to the Multiple Tube Method (Baird *et al.* 2017). The location with the worst quality water was chosen for later treatment trials.

2.2. Filtration experiments

2.2.1. Filter construction

The filter was constructed employing only commercial materials. Medium sand was used as a filtering agent and gravel as a support layer. The support layer was made of stone dust (<4.8 mm), gravel 0 (4.8 mm to 9.5 mm), gravel 1 (9.5 and 19 mm), and gravel 2 (19 to 25 mm). The filter column was built using 10 cm × 160 cm PVC tubes.

For the particle size study of the filtering material, a granulometry assay was performed. 1,000 g of material was sieved using sieves with 0.075; 0.15; 0.18; 0.30; 0.425; 0.60; 0.85; 1.00; 1.18; 2.00 mm opening. The results were used to define the mean grain diameter (d, given in mm), as well as the values of d_{60} and d_{10} (opening size (mm)) which retain 60 and 10% of the material, respectively). With these values, the uniformity coefficient (U.C.) was calculated according to Equation (1).

$$\text{U.C.} = \frac{d_{60}}{d_{10}} \tag{1}$$

The thickness of the filtering layer (L, given in mm) of the bench-scale filter was determined so that the dimensionless relation L/d would be equal to or higher than 1,000 (Di Bernardo & Dantas 2005). Furthermore, the thickness of each stratum in the support layer was: 9 cm for gravel 2 and 7 cm for gravel 0, gravel 1, and stone dust, arranged in this order vertically in a PVC pipe with 1.6 m in height.

2.2.2. Filtration rate evaluation

A feed tank with an adjustable valve was placed above the filter so it could operate downward. Different filtration rates (0.94; 2.96; 4.61; and 8.27 $m^3\ m^{-2}\ d^{-1}$) were applied and the best one was defined by turbidity removal efficiency (turbidimeter HANNA Instruments, HI 93703). A total volume of 5 L of feed water was filtered on each case.

2.3. Disinfection tests experiments

The disinfection tests aimed to determine the best time of water exposure to the sun. For this, six colorless and previously sanitized bottles of Polyethylene Terephthalate (PET), with a volume equal to 2 L, were filled with raw water up to 90% of the total volume and exposed to the sun through a solarizer, constituted of support of wood and a corrugated zinc sheet in a rectangular form. Sunlight exposure of 2, 4, 6, 10, 12.5, and 25 h were evaluated, in each one of the samples were collected and analyzed to determine the removal of total coliforms and *E. coli*, according to Standard Methods (BAIRD *et al.* 2017). On experiment days, sunrise and sunset time were 05:29 and 17:56, respectively. On the first day, the experiment began at 08:00, and samples of 2, 4, 6, and 10 h of sun exposure were collected at 10:00, 12:00, 14:00, and 18:00, respectively. On the second day, at 8:00, and the sample related to 12 h total sun exposure was collected. Finally, on the third day, the 25 h sun exposure sample was also collected at 08:00.

Tests were carried out in Belo Horizonte – Minas Gerais – Brazil (Latitude: 19°48′57″ South, Longitude: 43°57′15″ West). The solar incidence was monitored with a solar radiation meter KOPP&ZONEN DELFT/HOLLAND, model CM6B, and the total accumulated energy was calculated.

2.4. Pilot-scale system construction and operation

A prototype of the treatment system, consisting of slow filtration applying sand as a filtering medium and gravel as support, and disinfection using solar radiation, was built in a pilot scale, as shown in Figure 1. Only low-cost materials were employed.

Figure 1 | Simplified prototype of treatment water system.

The system was dimensioned for a 12.5 L supply of water per day and was operated in batch mode. Each batch lasted for 3 days (one day for filtering and two for disinfection), producing a total of 37.5 L of treated water for this period.

Operation conditions were the ones established in bench-scale tests. The filtration rate was 2.4 $m^3\,m^{-2}\,d^{-1}$, which was defined using the results of experiments aiming at filtered water turbidity of 5 UNT. The number of PVC tubes used was calculated considering this filtration rate, with tubes of 10 cm of diameter and flow of 12.5 $L\,d^{-1}$, which means two tubes per system. Each one of these filters was built according to the results found in the bench filtering tests.

To disinfection, 20 bottles of 2 L were connected in series by transparent hoses and fed by the filter. After the desired exposure time, treated water was manually removed from the system.

The filter was operated in two batches, each one treating 37.5 L of raw water from Pau de Cheiro Stream. The first batch was used only for the adaptation of the system. On the other hand, during the second batch, turbidity, total coliforms, and *E. coli* were monitored for raw water, filter output, and water after disinfection.

In addition, two 500 mL treated water samples were kept in fresh PET bottles for a week. A sample was kept in a fridge at 2–10 °C, while the other was kept at room temperature. Both were analyzed for total of coliforms and *E. coli* after the period of storage.

3. RESULTS AND DISCUSSION

3.1. Filtration tests

3.1.1. Filter design

Figure 2 shows the granulometric curve for medium sand.

The mean particle diameter was equal to 0.773 mm. The d_{60} and d_{10} found were 0.90 and 0.25 mm, respectively, which results in a uniformity coefficient of 3.60. Although the result for d_{10} is within specification for slow filtration, the uniformity coefficient is out of standard (<3) (Cumbi 2013) because of the high d_{60}. However, aiming at prototype scalability facility and practicality, no change on particle size was made so that users could apply the materials as usually found in construction materials stores.

Respecting the relation $L/d \geq 1{,}000$ (Di Bernardo & Dantas 2005), and being $d = 0.773$ mm, the bench filter was designed with $L = 1$ m.

3.1.2. Evaluation of the best filtration rate

The relation between turbidity removal and filtration rate is shown in Figure 3. The feed water average turbidity was 174 UNT.

The results obtained show the efficiency of the filter in reducing the turbidity of the water, even though raw water turbidity was high. Efficiencies ranged from 99.8 to 93.8%, showing a reduction when the filtration rate is increased. However, even with a filtration rate of 8.27 $m^3\,m^{-2}\,d^{-1}$, which is higher than the recommended for slow filters, the system was able to reduce the water turbidity to less than 30 UNT, a suitable value to feed the disinfection system (Wegelin 2006).

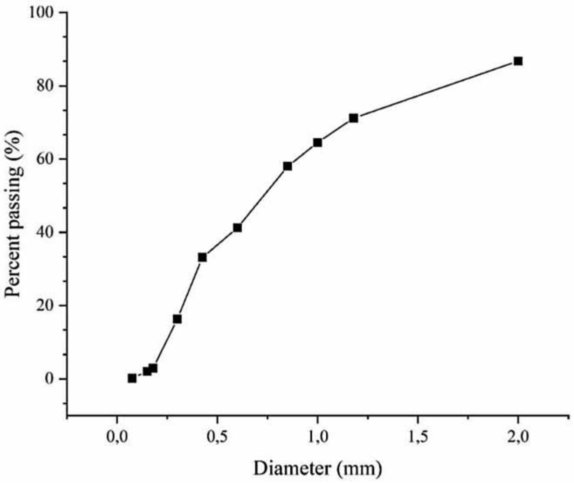


Figure 2 | Granulometric curve for commercial medium sand.

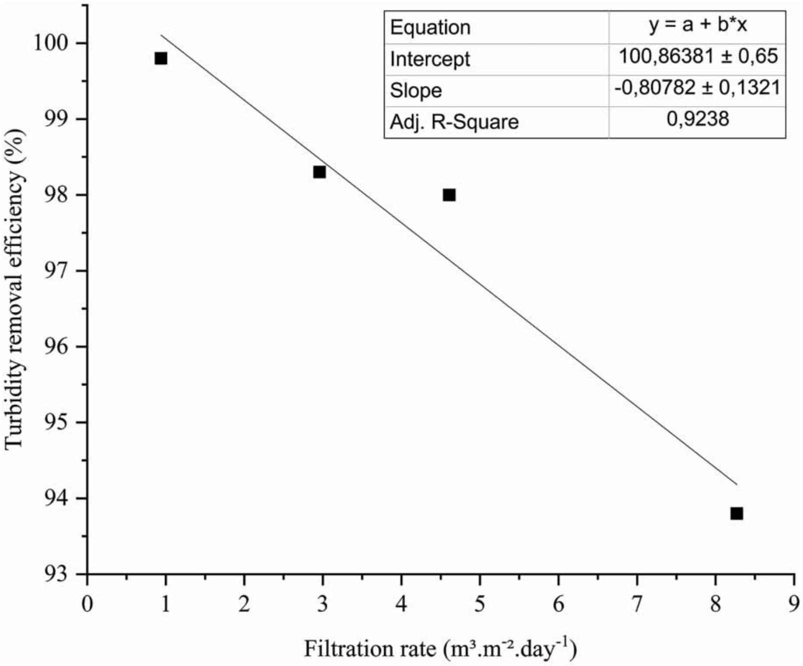


Figure 3 | Relation between turbidity removal and filtration.

The filter must also be able to reach the potability standard of <1.0 UNT for water after slow filtration. However, the Brazilian Ministry of Health established that according to an organoleptic standard of potability, turbidity values up to 5 UNT are acceptable, not causing harm to health (Brazilian Ministry of Health 2017). By a mathematical adjustment applied to the data in Figure 3, it is observed that the filtration rate of 2.4 $m^3 m^{-2} d^{-1}$ can remove about 99% of turbidity. For feedwater with a turbidity of up to 500 UNT, the maximum value found in several samples taken from Pau de Cheiro stream, the efficiency related to 2.4 $m^3 m^{-2} d^{-1}$ can lead to treated water turbidity less than 5 UNT.

3.2. Disinfection tests

Figure 4 shows the results of total coliform and *E. coli* removal efficiency and cumulative solar irradiance as a function of sun exposure time.

The *E. coli* seems to be more sensitive to the solar disinfection treatment compared to total coliforms, showing higher removal efficiencies at the same period. Similar results were found by Carvajal (2015). Also, the MPN reduction rate of living organisms was adjusted to a pseudo first-order model, according to Chick's Law. The first-order kinetic constant found was $0.74 \pm 0.11\ h^{-1}$ for *E. coli* and $0.30 \pm 0.02\ h^{-1}$ for total coliform, which means a faster decay for *E. coli*.

It is possible to note a relationship between sun exposure time, cumulative solar energy, and bacteria removal. Exposure to the sun for 25 h is enough to reduce the total coliform concentration by 99.9% and *E. coli* by 98.7%, reaching results of 1 MPN.100 mL^{-1} on both cases. Although high, these values are lower than others found in the literature. For example, Boyle *et al.* (2008) report 4 log units of removal of *E. coli* with 1,050 W/m^2 of maximum irradiance in 90 min, and Berney *et al.* (2006) found 90% removal of *E. coli* in about 3 h. Dessie *et al.* (2014) found a first-order decay constant equal to 1.22 h^{-1} for total coliforms. The lower efficiencies found in the present work could be due to the high turbidity on feed water, of 43.0 NTU, which interferes in sunlight absorption. Studies of Dessie *et al.* (2014) confirmed that higher turbidity decreases the disinfection efficiency considerably. According to the authors, in 3 h of exposure, removal of 0.93 log unit was obtained for water with a turbidity of 2 NTU, while just 0.05 log unit was found for water with 81 NTU. Another factor that can negatively influence the bacterial inactivation process by solar irradiation is the presence of inorganic ions, commonly found in surface water, which may occupy part of the contact areas between the membrane cell and the oxidative species. In addition, the anions negatively affect the osmotic stress, which generates a preferential flow of water from inside the cells to the medium (Rubio-Clemente *et al.* 2019).

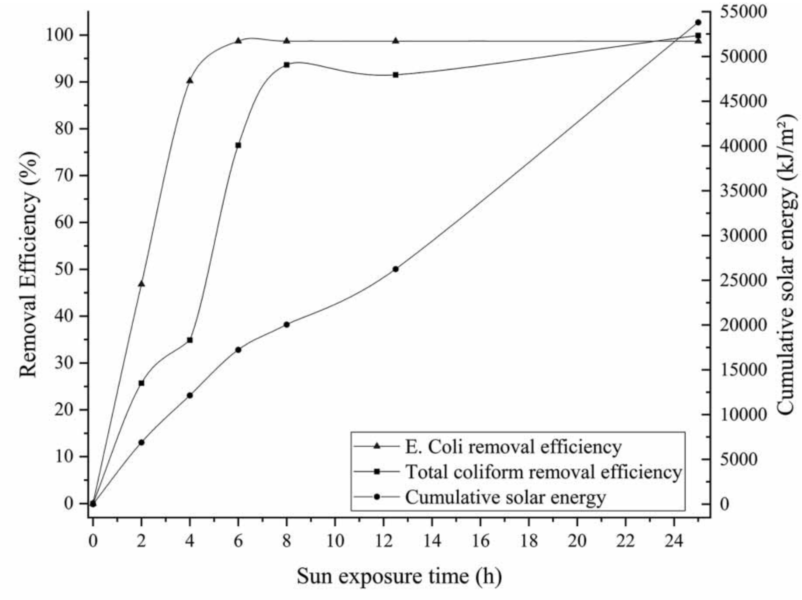


Figure 4 | Total coliform and *E. coli* removal efficiency and cumulative solar irradiance over the sun exposure time.

The regrowth process may have happened, evidenced by the increase in the total coliform MPN and reduction in their removal efficiency overnight (between 10 and 12 h of exposure to sunlight). On the other hand, *E. coli* did not show signs of regrowth. To avoid regrowth, oxidizing reagents, such as H_2O_2, could be dosed to water since it causes severe damage to bacterial structures, making their inactivation irreversible (Langenbach *et al.* 2010; Rubio-Clemente *et al.* 2019). However, as the use of chemical oxidizer would increase the cost of the process, it would be better not to store the treated water, or at least store it for short periods in refrigerated environments, since any residual bacterial trace could make it inappropriate for human use (Vivar & Fuentes 2016).

To achieve high removal efficiencies, 25 h of sun exposure to the sun (48 consecutive hours) was chosen time for the pilot-scale tests.

3.3. Building and operation of the prototype

Table 1 shows the results of the pilot-scale water treatment system.

It could be noted that the filtration provided high removal not only for turbidity but also for microorganisms. Disinfection, on the other hand, promoted almost total removal of the remaining bacteria in the medium.

The substantial removal of bacteria on the filter supports the theory that slow filtration also functions as biological filtration. This is because, as the water retention time in the filter is long, bacteria from raw water can adhere and colonize the upper layers of the filter (Mushila *et al.* 2016). This attached biomass removes contaminants and organic matter present

Table 1 | Results of the monitoring of raw and treated samples in the pilot-scale water treatment system

		Samples		
Parameter		**Raw**	**Filter output**	**Final treated water**
Turbidity	Value (NTU)	50	1.2	1.2
	Removal efficiency	n.a.	97.6%	97.6%
Total coliform	Value (MPN.100 mL^{-1})	1,011	22.8	<1
	Removal efficiency	n.a.	97.7%	>99.9%
E. coli	Value (MPN.100 mL^{-1})	114	<1	<1
	Removal efficiency	n.a.	>99.1%	>99.1%

n.a., Not applicable.

in the water through the process of sorption and biological degradation. The rate of bacterial population growth at the top of the filter is limited by the amount of organic matter provided by the feed water and gradually decreases with depth as food and oxygen became scarce (Cumbi 2013). It is possible that the first batch, held to adjust the system operation, had favored the formation of the organic layer and increased removal of microorganisms.

To investigate bacterial regrowth indicated by disinfection tests, treated water samples were stored for 7 days under two conditions: at refrigerator and room temperature. The first showed no bacterial growth, revealing, after 7 days of storage, the same coliforms, and *E. coli* concentrations of the just treated water (<1 MPN.100 mL^{-1}). As for those stored at room temperature, the result was 1 MPN.100 mL^{-1} of total coliform, indicating that the microorganisms can regrowth, even if at a low speed. The growth of bacteria after SODIS treatment can occur whenever there are residual bacteria that have not been irreversibly inactivated, depending on the availability of organic matter, temperature, light, storage time, and handling of the containers, which reinforces the need for total disinfection and adequate storage (Vivar & Fuentes 2016).

Regarding the economic aspects of the project, the total cost of the system for one person's water needs (production of 37.5 L every 3 days) was USD 28.79, including all the necessary materials. It is known that the slow filtration system requires only cleaning as filter maintenance (Cumbi 2013), which consists of simple scraping of the superficial sludge, every 2 months, in addition to a small replacement of sand, proportional to the amount removed during this cleaning procedure. Thus, once the filter is assembled, its service life is indefinite.

Compared with other commercial domestic water treatment systems, the proposed setup is considerably cheaper. In Brazil, a commercial water purifier costs around USD 122, and the media must be replaced after 3,000 L filtered, which adds a variable cost of USD 20 to the operation. That makes water purifiers less accessible for low-income communities. Regarding alternative treatment systems, Mwabi *et al.* (2013) studied different cost-effective household water treatment systems for low-income communities, like ceramic candle filters, biosand filters, and silver-impregnated porous-pot filters. The ceramic candle filter and the biosand filter cost around USD 33 and USD 10, respectively. Despite their low costs, both could not reach potability standards. The silver-impregnated porous-pot filter was the only one that produced safe drinking water, costing around USD 17. The disadvantages of that technology pointed by the authors are the need for pre-treatment, periodical maintenance and cleaning, and its short lifespan. Also, the materials are not easily found in local stores in small communities. Considering all of it, it is believed that the cost of the system proposed in this paper is competitive. Still, it is noteworthy that in addition to bringing significant improvement to the quality of life, the proposed system can also provide a considerable reduction in medical expenses and the purchase of bottled water.

Regarding the bottles, although the degradation of PET due to its exposure to the sun may generate unwanted substances, Wegelin *et al.* (2001) showed that the compounds are formed on the outside of the bottle and the water remains without traces of contaminants. Still, Schmid *et al.* (2008) took into consideration the recycling of the bottles, their origin, and the temperature during the process, and found that the concentration of toxic substances such as di(2-Ethylhexyl)adipate (DEHA) and di(2-Ethylhexyl)phthalate (DEHP) remained below acceptable values for water for human consumption, which enhances the security of the SODIS application.

4. CONCLUSION

The development of the present study took place after a critical analysis from the social point of view, with an emphasis on public health, in relation to the consumption of untreated water, which still affects some communities. An alternative system for water treatment, composed of filtration and solar disinfection, was applied for water collected in a stream from a small municipality in Brazil. This work satisfactorily demonstrated the possibility of developing a low-cost decentralized water treatment system.

The slow filter consisting of sand and gravel showed high efficiency for filtration rates between 0.94 and 8.27 $\mathrm{m}^3\ \mathrm{m}^{-2}\ \mathrm{d}^{-1}$, leading to turbidity removal efficiencies from 93.8 to 99.8%. A filtration rate of 2.4 $\mathrm{m}^3\ \mathrm{m}^{-2}\ \mathrm{d}^{-1}$ was chosen to allow filtered water turbidity lower than 5 NTU – meeting the organoleptic standard of potability of the Brazilian Ministry of Health. After 25 h of sun exposure time (48 consecutive hours), 99.9% of total coliform and 98.7% of *E. coli* were removed. *E. coli* decayed faster than total coliforms.

In pilot-scale experiments, removal efficiencies higher than 97% for turbidity and 99.1% for *E. coli* were observed. These results show a successful transposition of the system proposed on the bench to the pilot scale. Furthermore, the slow filtration seemed to also work as biological filtration, as it was able to remove total coliforms and *E. coli* in the sand media. Regrowth of bacteria, which was observed in bench-scale solar disinfection experiments, was controlled when the treated water sample was stored in a refrigerator.

The system for a four-people house costs around 116$. Although it may represent a significant value, the system would provide numerous benefits in terms of health and quality of life. Moreover, the proposed system could be easily applied in daily life, due to the simplicity of manufacture and high accessibility of the materials.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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