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Automated household-based water disinfection system for rural communities: Field trials and community appropriation

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A R T I C L E I N F O

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A B S T R A C T

This research involved a pilot field trial of household-based water treatment and storage for potable water in rural communities of Colombia and Mexico. Through co-creation with the communities, key parameters were considered when designing the systems, including the efficiency of disinfection, the provision of a sufficient volume of treated water, variability of the raw water quality and access to freshwater sources. The water treatment systems were automated with electronic controllers. They consisted of a sedimentation tank (bottom), a treatment unit (pre-filtration followed by UVC disinfection), a pump to move the treated water to a second elevated tank for storing the treated water (150 L or 250 L), and a small distribution network that provided water inside the home by gravity (kitchen and bathroom taps). They were installed at households in rural communities of Colombia (52 systems) and Mexico (187 systems) and the performance was evaluated over 12 consecutive months. Efficiency was evaluated using standard microbial and physicochemical water quality parameters. Treated water turbidity was below the World Health Organization (WHO) recommendation (< 5 NTU) in >97 % of the samples in Colombia and 98.9 % in Mexico. The treatment reduced *Escherichia coli* to potable levels in all cases, regardless of the initial microbiological load and the variation of the raw water quality. In some cases, an increase in *E. coli* values was detected in the distribution network within the households (post-storage), although not statistically significant, they represented a 'moderate risk'. The health risk associated with the water was reduced to 'low risk' in >80 % of the treated water samples vs. <10 % before treatment. After 12 months of operation, the household water treatment and storage systems (HWTSs) remained effective for the provision of potable water.

1. Introduction

Although progress is being made towards SDG6, in 2022, 2.2 billion people still lacked safely managed drinking water, including 1.5 billion with basic services, 292 million with limited services, 296 million with unimproved and 115 million drinking surface water (UNICEF-WHO, 2023). Contaminated water and poor sanitation are among the leading causes of death for children under 5 (UNICEF, 2023). Socioeconomic and geographical limitations make very difficult the implementation of standard drinking water and sanitation facilities and infrastructures in low-income and vulnerable areas. These are mainly rural communities that often use unimproved water sources (Prüss-Ustün et al., 2019).

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According to the United Nations Assembly, every person must have access to enough water for personal and domestic uses (UN, 2010). The UN Sustainable Development Goal 6 – Water and Sanitation for All, established the SDG indicator 6.1.1, which tracks the proportion of the population using safely managed drinking water services. This indicator measures the percentage of people who have access to improved drinking water sources that are: (1) located on the premises, (2) available when needed, and (3) free from faecal and priority chemical contamination (UN, 2022). It has been demonstrated that increasing the quantity of water available for consumption and hygiene is one of the most efficient interventions to reduce the risk of waterborne diseases in low and middle-income countries (LMICs), which is linked to water supply accessibility (Cassivi et al., 2019).

In rural areas of LMICs, water accessibility and quality strongly depend on geographical location and weather seasonality, which also determines the water culture and practice of the communities around domestic water (Cassivi et al., 2019; Cronk et al., 2024). Decentralised Household Water Treatment and Storage systems (HWTSs) have been recognised as a sustainable approach to improve access to drinking water in these areas (Prüss-Ustün et al., 2019). Their correct and consistent use, and in combination with basic sanitation services, are associated with improved water quality indicators and increased reductions in the risk of diarrhoea in children (Wolf et al., 2022; Cassivi et al., 2019).

Treated water should follow the WHO drinking water quality standards (WHO, 2022). This can be guaranteed when treated water is periodically monitored in centralized water supply systems. In the case of non-routine water quality monitoring in place (for decentralized HWTS and point-of-use systems), they must provide comprehensive protection against microbiological contamination (WHO, 2019). The WHO recommended sampling and monitoring turbidity, free chlorine (if using chlorination), and microbiological quality via *E. coli* or thermotolerant coliforms, as indicators of faecal contamination before and after the treatment and periodically after the intervention; at least 1–2 times per year, capturing seasonal variability, or once per 1–3 months if there is capacity (WHO, 2024).

There are only a few HWTSs which meet the WHO standards for protecting water sources. These are boiling and pasteurization, chlorination and flocculation, ceramic filtration, household slow-sand filtration, solar disinfection, UV disinfection, and adsorption on activated carbon. Nevertheless, there is not a single HWTS solution that is appropriate for all contexts. The number one priority for selecting a technology should be the microbial safety of the water, followed by other factors that influence correct and consistent use, including technology availability, sustainability, cost, and user acceptance (WHO, 2024). The lack of correct and consistent use of HWTS has been widely reported (Amrose, Burt and Ray 2015). Water interventions in LMICs, based on chlorination, provide safe drinking water and storage at the household level (Solomon et al., 2020) but fail to be used consistently and correctly. Automated chlorinated systems have been found to be promising in Bangladesh and Nepal, but with significant problems of in-home recontamination (Lindmark et al., 2022). However, chlorinated water is usually unpopular due to taste and odour and is rarely consumed, therefore not producing the expected benefits in the community (Wolf et al., 2022; Aiken et al., 2011; Clasen et al., 2007). Other HWTS technologies have been commonly reported as drinking water interventions using other methods or technologies, including bio-sand filters (Aiken et al., 2011), nylon filters (Colwell et al., 2003), ceramic filters (Brown et al., 2008), pasteurization (Ijima et al., 2001), UV disinfection (Reygadas et al., 2015), solar disinfection (Conroy et al., 1996), boiling (Clasen et al., 2008a, 2008b; Rosa et al., 2010; Shate et al., 1996) or their combination e.g. sand filtration followed by chlorination (Howard et al., 2006). These works highlight that correct and consistent use is key; therefore, the use of automated systems, although more costly, could be an advantage for adoption and sustainable use.

The quality and impacts of water interventions are determined by the acceptability, adoption, compliance, and sustained use (Chaúque et al., 2023). High adoption and usage compliance (>90 %) lead to a substantial reduction in the risk of waterborne diarrhoea, even in cases of limited microbial removal efficiency. The factors that influence "how an intervention program is implemented", which are context-specific and dependent, have been systematized and identified as either barriers or enablers (Chaúque et al., 2023). This analysis pointed out the cost of products and the lack of available spare components (for the technology/product) as the major barriers, and the best enabler was the user demand and partnerships for HWTSs implementation (Chaúque et al., 2023). Hayashi et al. (2019) proposed a framework to model the links between quantitative microbial risk assessment, technology efficacy and end-user compliance behaviour and environmental factors for waterborne disease interventions. Interestingly, this study recommends focusing on cost-efficient and readily usable treatment options (Hayashi et al., 2019). Enger et al. (2013) analysed the effectiveness of HWT on childhood diarrhoea incidence via drinking water using a quantitative microbial risk assessment model. They observed that for perfect compliance, diarrheal incidence decreases as bacterial log reduction values (LRVs) increase. However, when compliance is incomplete, higher LRVs are more beneficial if contamination spikes are large, contamination levels are generally high, or some people comply perfectly. When the effectiveness of HWT interventions at the community level is limited by imperfect compliance, then the benefits of high LRVs are not reflected (Enger et al., 2013). Therefore, any drinking water intervention might consider these aspects as key to succeed in compliance for reaching high impact in the communities and longevity of the technology in the field.

Lane et al. (2023) proposed an adaptation of a triple-bottom-line approach for examining technology alternatives in small community water systems. They concluded that for point-of-use and point-of-entry (POU/POE) systems, it is necessary to consider securing 100 % community participation, running pilot tests of devices, sampling for compliance, sourcing devices locally, understanding state guidance on POU/POEs and ensuring ongoing operational and maintenance activities. These recent findings are totally in line with the methodology used in this research.

This work aimed to implement an intervention that considers technology acceptance and appropriation by the communities, locally available components, water quality monitoring, water provision to meet users' demand, and maintenance and training to ensure long-term use, which is highly recommended but also extremely demanding. This scientific, technical, and social mission required the combined efforts of a trans-disciplinary research team that held expertise in drinking water quality and treatment, and social sciences. This research aimed to investigate the performance of 239 HWTSs (filtration followed by UV disinfection) installed at households in rural communities in Antioquia, Colombia (52) and Chiapas, Mexico (187) and evaluated over 12 consecutive months. The HWTSs systems were automated with electronic controllers. They consisted of a sedimentation tank (bottom), a treatment unit (pre-filtration followed by UVC disinfection), a pump to move the treated water to a second elevated tank for storing the treated water, and a small distribution network that provided water inside the home by gravity (kitchen and bathroom taps). Different aspects were evaluated to analyse the long-term sustainability of the technology in the target communities: technology availability and cost locally, users' drinking water demand, and technology's long-term performance for providing safe drinking water.

2. Methodology

2.1. Study sites – colombia and mexico rural communities

The study was performed in two rural communities of Colombia, and one in Mexico. In Antioquia (Colombia) the communities of Curití (Liborina; 6°40′59′'N, 75°48′0′'W) and El Carmelo (El Peñol; 6°13′08′'N, 75° 14′31′’ W) were studied. Details of the locations and areas where this intervention took place are given in the Supplementary Materials (Figure S.1). Their primary economic activity is agriculture and livestock. Curití is supplied by surface water from streams, while El Carmelo is supplied from a micro-basin. All households are supplied with untreated piped water. The vast majority boil the water as a preventive measure before consumption. The average number of persons per household in Colombia was 4.7 and 68 % of households had children under 5 years old. The houses had a functional water-based toilet piped to septic tank. In Mexico, the community of Chimix, located in the indigenous region of the Highlands of Chiapas (17° 0′ 14.4054″N, 92° 30′ 59.26788″W), was evaluated. It lacks basic services such as piped water or sewerage. They are supplied from multiple sources (i.e. harvested rainwater, surface water and spring water) for domestic use, and fetching water is a common and frequent practice. Boiling is the only treatment method reported by the community, although it is not carried out regularly. The average number of persons per household in Mexico was 5.9 and 50 % had children under 5 years old. In Chiapas, sanitation practices vary, with household pit latrines being the most common.

2.2. Description of the intervention

A total of 239 HWTSs were installed in the rural communities of Curití, El Carmelo (Colombia) and Chimix (Mexico). The intervention included: i) engagement of families where the technology was implemented via local workshops and public presentations; ii) Installation at the households of HWTSs (Section 2.3); iii) training events and one-on-one training sessions with the household members to operate and provide basic maintenance; iv) training of community technicians to conduct out repairs; v) periodic follow-up visits for water quality monitoring and technical checks.

2.2.1. Selection criteria

The primary selection criteria for the communities were the lack of access to safe drinking water on the premises, access to sufficient water for treatment, and their willingness to participate. In both countries, contact with communities was established through local leaders and/or water management committees (who dealt with water issues). Once selected, local workshops and meetings between researchers, local authorities, and engaged families were held to introduce the project and agree on the terms and consent to the implementation (Supplementary Materials, Figure S.2), following the ethical guidance for field trials involving human participation (registered at clinicaltrials.gov with ref. NCT04829981(Colombia) and NCT04736615 (Mexico)). This had different implications in the household selection for both countries due to their contexts. In Mexico, to be able to participate in the trial, the households had to have access to sufficient water (which they normally carried from a nearby source), an electricity supply, and space in their yards. While the Colombian communities already had untreated piped water and electricity supply in all households.

2.2.2. Installation of HWTSs

Pilot and feasibility testing of HWTS systems was conducted in 3 households in Colombia and 3 households in Mexico for six months before the main field trial to assess their functionality, cultural appropriateness, and other field factors. HWTSs (52) in Colombia and HWTSs (187) in Mexico were installed and set up at each selected household. Then, several training events were organized to create and grow the capacities to use and manage the HWTSs, including basic maintenance (Section 2.4) and understanding the functioning of the automated HWTSs, i.e. how the controller filled the empty treated tanks, indicated when an UV lamp had a failure, and made sure there was always sufficient treated water. This activity was carried out from March 2021 to May 2021 in Colombia and March 2021 to April 2022 in Mexico.

2.3. SAFEWATER HWTSs

The SAFEWATER (SW) HWTSs installed at household level in Colombia (SW-C) and Mexico (SW-M) consisted of a sedimentation tank, a treatment unit, a second tank for storing the treated water, and a small distribution network (Pichel et al., 2021) (Fig. 1). The sedimentation tank was located at the bottom of the supporting structure. Raw water was pumped from the sedimentation to the treated water tank through the treatment unit using a diaphragm pump at 3 L min^{-1} (Seaflo SFDP1–012–035–21 China in SW-C, and Shurflo SLV10-AA41 USA in SW-M). The treatment consisted of filtering through two pleated thermofused polypropylene filters (5 and 1 μm) (SPC-25–105 and SPC-25–1001 Hydronix, USA) and a UVC disinfection reactor (16W-LP lamp, 5.2 mW/cm^2, λ=254 nm) (UV-16 W EVANS®, Mexico). Treated water was safely stored in a closed tank located at the top of the structure at a sufficient height to allow gravity-fed water distribution to the house. The treated water was then distributed through piping inside the household’s main consumption sites, at least two taps located throughout the home premises (kitchen and bath), to facilitate drinking water access. The SW-HWTSs were installed outdoors the treatment units were enclosed in a cabinet (Fig. 1.c) for protection of the electrical components. To reduce user dependence on the technology and to alert the user to failures, an electronic controller was designed and incorporated.

The controller was activated by float switches in the raw and treated water tanks. The system automatically activated once the low level in the treated water tank was reached and stopped when the fill level was achieved. The controller had alarms for failures, including a maximum run time alarm which indicated that either there was a pump failure, or the filters were blocked. The controller was also alarmed if there was a failure in the UVC unit (Supplementary Materials, Figure S.3). Under this operation, the households always had sufficient treated water in the storage tank (as long as they had sufficient water in the raw water tank) and the system operated for one cycle until the low level float switch in the treated water tank was activated again i.e. the water in the treated tank had been consumed. Water availability and access were different in each country; therefore, tank capacity was selected to best adapt to the community’s needs. In Colombia, access to sufficient water was not an issue. However, Mexican communities have a great need for storage, as they face frequent water shortages and must fetch water from long distances. Therefore, 150 L tanks were installed in Colombia (Fig. 1.a), and 250 L tanks in Mexico (Fig. 1.b).

2.4. HWTSs maintenance – community training

Community volunteers and local technicians were trained in the communities to give basic guidance to end-users on how to operate and maintain the HWTSs installed. Once every 15–30 days, depending on the raw water quality, maintenance activities were carried out. This consisted of cleaning and disinfecting the tanks and taps using common and accessible items such as sponges or cloths and sodium hypochlorite solution. To remove residual chlorine from tanks and taps after disinfection, consecutive rinses with treated water were undertaken, followed by the discharge of rinsing water. This was consistently explained to the communities using basic infographics (Supplementary Material, Figure S.4) in local training workshops. The filters were replaced by new ones every 3–4 months. HWTSs were repaired when users or follow-up visits detected a failure, this included controllers’ breakages due to electric storms, UV lamp failures, etc.

2.5. Field study design

In Colombia, a longitudinal study was carried out with the 52 HWTSs installed (36 in Curití and 16 in El Carmelo), which were then monitored monthly over 12 months from June 2021 to May 2022. Due to the large size of the Mexico field trial, 187 HWTSs were installed in 7 stages

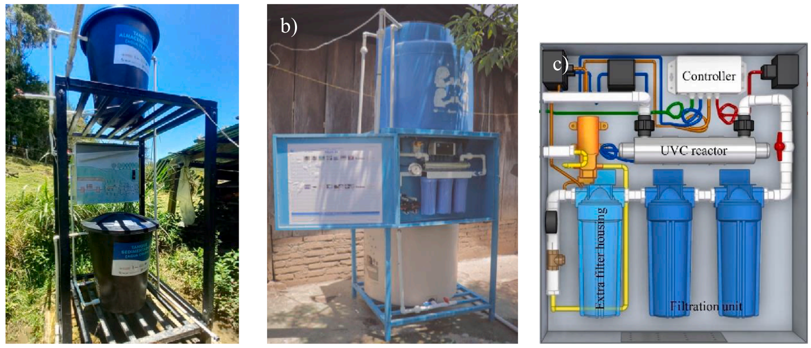

Fig. 1. SAFEWATER HWTSs installed in rural communities of Colombia and Mexico with supporting structure, sedimentation (bottom) and storage (top) tanks and the enclosure box. A) SW-HWTSs in Curití (Antioquia); b) SW-HWTSs in Chimix (Chiapas); and c) Diagram of the treatment unit enclosure case with main elements.

separated by 2–3 months due to logistics and long journeys required to reach the communities (Figure S.5 – Supplementary materials). Due to the remote location of the communities in Chiapas, 20 households were randomly selected in stage 1 to be monitored for 12 months, from July 2021 to June 2022. This permitted a follow-up of their performance during the entire season.

2.6. Water quality analysis

Conductivity, temperature, pH, turbidity, and transmittance at 254 nm (UVT_{254}) were analysed before (SP1) and after (SP3) treatment, while *E. coli* and total coliforms (TC) were measured in all sampling points (SP1 - SP5) (Fig. 2). The methods and equipment used are shown in Table S.1 (Supplementary Materials).

2.7. Water sample collection and monitoring

Monthly visits to the HWTSs were made to monitor water quality. Water samples were taken from the raw water tank (SP1), after the UVC unit (SP2), the treated water tank (SP3), the kitchen tap (SP4) and the bathroom or hygiene setting tap (SP5) (Fig. 2). SP2 was monitored to test the efficacy of the UVC lamps, showing a complete absence (below the detection limit: BDL) of *E. coli* in all samples of this study. Potential water recontamination at the point of use was investigated through SP4 and SP5. The cumulative consumption of treated water was recorded every month using a rotameter (CAMM10 R10, Water Meter Corporation).

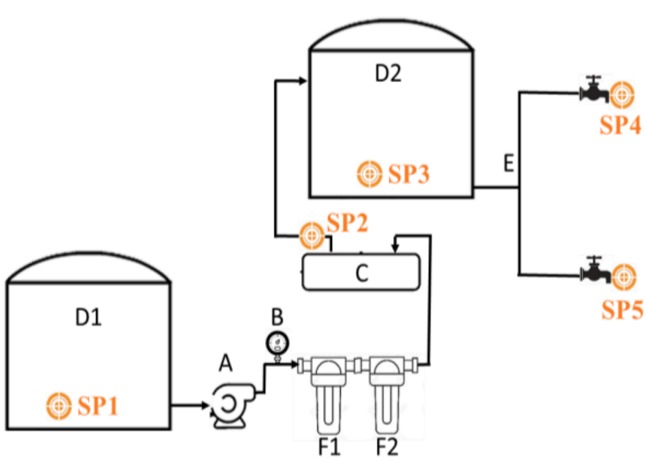

Fig. 2. Sampling points (SP): Raw water (SP1), after UV disinfection (SP2), treated water (SP3), kitchen tap (SP4) and bathroom or hygiene setting tap (SP5). Main components: raw water tank (D1), pump (A), pressure gauge (B), filters (F1, F2), UV lamp and controller (C), treated water storage tank (D2) and distribution network (E).

2.8. Statistical analysis and water health risk factor

Water quality data were analysed and summarised based on descriptive statistics, average, standard deviation, minimum, median, and maximum. Samples with values below the detection limit (DL) were included in the statistical analysis by assigning them the exact value of the DL. Normality distributions were evaluated by the Shapiro-Wilk test (p<, 0.05 is non-normal, and $p > 0.05$ is normal, 95 % confidence level). The paired non-normal datasets were compared using the non-parametric Wilcoxon test and the unpaired non-normal datasets using the non-parametric Mann-Whitney. The difference between means (parametric tests) and between medians (non-parametric tests) was considered significant for $p < 0.05$ (95 % confidence level). Bivariate analysis (Spearman's correlation test) was made to investigate whether there was a cause-effect relationship between *E. coli* counts at SP3 and the auxiliary variables (turbidity, UVT_{254}, *E. coli*, TC, cumulative treatment volume, frequency of changing filters, lamps, pumps, tanks and controllers). For bivariate analysis, the significant correlation was defined at $p < 0.05$, and the module of Spearman coefficient $|r| > |r\text{-critical}|$. Statistical tests, including descriptive statistics, hypothesis tests and bivariate analyses, were performed on PAST 3.25 software. The water health risk factor was calculated and classified according to WHO recommendations (WHO, 2024). Based on the *E. coli* counts (in CFU/100 mL or MPN/100 mL), the treated water was considered of low risk for numbers between 0 (or below DL) and 1; moderate risk from 1 to 10; high risk between 10 and 100; and very high risk for counts >100 (WHO, 2024).

2.9. Prototype cost analysis

Initial investment and annual operation and maintenance costs of the HWTS were evaluated in both countries. Initial investment included the main HWTS components (i.e.: tanks, pipes, fittings, valves, pump, metal structure, UV system, filtration cartridges, electrical components, labour and control box) budgeted for 1st October 2020. The values were updated to 1st December 2024 using the annual Consumer Price Index (CPI) from Mexico and Colombia. After the update, the amounts were shown in American dollars (USD).

Operation and maintenance costs involved monthly electricity consumption, changing filtration cartridges every three months, UVC lamp replacement every 5 years, and cleaning the systems (tanks and pipes) once per month. This would mean the allocation of labour costs equivalent to one day per year for each HWTS system, costed by the basic salary wages in Colombia (11.11 USD day^{-1}) and Mexico (14.20 USD day^{-1}) in Jan 2025.

The estimated cost per litre was determined for the HWTS, with the present value of all items and calculated with a production of 150 L per day. This average treatment capacity was designed based on feedback from the communities. However, the systems were automatic and would provide as much treated water as necessary, as long as there was water in the raw water tank. Our surveys on water use in the communities indicated that Colombian communities would consume around 50 L $person^{-1}$ day^{-1}, while the Mexican households reported between 10 and 20 L $person^{-1}$ day^{-1}, which can be explained by their easy access to water resources in Colombia and the difficulties in accessing water resources in Mexico, involving in some cases of having to walk long distances and taking water from various resources.

3. Results and discussion

3.1. Community approach

Communities in Mexico were all of indigenous ancestry and, compared to Colombia, had a higher mean number of household members (5.9 vs 4.7), and were more likely to have children under 5 (68.2% vs 50%). Although from a much more socioeconomically deprived area than Colombia, respondents in Mexico were more likely to own the house where they lived (90 % vs 50 %). However, they were more reliant on agriculture and livestock for a living (85 % vs 63.6 %), no households had a toilet and less than half had a latrine (45 %), where often ashes were used to cover faeces, compared to Colombia, where all households visited had a functional water-based toilet. Piped water was available to most (85 %) households in Mexico households, although this was usually located outside the house, whereas in Colombia running water was available inside all households. In Colombia, they were more likely to have received formal education at secondary level or higher (54.5 %), compared to those in Mexico (10 %). In the Mexican communities there is widespread distrust toward government-led health promotion efforts. As a result, the population does not perceive water quality as a health concern and generally does not believe their water is contaminated. During the baseline visit, 76 % of families reported perceiving their household water as safe, and only 44 % reported having treated it in the previous week. Among those who did treat their water, 96 % relied on boiling as their primary method. The new water system would not only treat the water, but it would improve accessibility by delivering it to key points within the home. This enhanced convenience emerged as the main benefit perceived by the community and was the primary motivation for most families to participate in the program.

At the very beginning of the project, various local workshops and meetings were held between researchers, local authorities, and participating families to understand existing water treatment practices (if any), assess their willingness to try new technologies, and introduce the project and obtain consent for its implementation. According to anecdotal feedback received before the intervention, there was distrust in the communities and a reluctance to shift paradigms because they had traditionally boiled water for drinking. The community's interest in adopting the HWTS, and receiving corresponding training grew once the project was fully described and the benefits demonstrated to them, including a study leaflet in the local language. Meetings held with the communities made evident that, despite their awareness of the need for safe drinking water, there was a lack of perception of the link between water contamination and health risks, as raw water was used daily in critical activities such as drinking and personal hygiene (observed during field visits). Some authors have shown that the lack of awareness of the risks of using poor-quality water and the cost of safe water can result in poor decision-making (WHO, 2019). In this regard, community engagement was not easy at first. As Roldán-Rojas and Megerle (2023) reported, the perception of water quality and health risk influences the implementation process of drinking water systems. The perception of the organoleptic quality of raw water in the rural communities studied was between good and acceptable, with turbidity being the most unfavourable parameter, followed by colour. They considered that the quality of the water used for cooking and personal hygiene must be excellent or good, for washing clothes and animal feed must be good, and for cleaning the house, gardens and crops, moderate quality (observations during field visits).

Boiling was the most common treatment method, despite not being performed regularly; therefore, raw water was sometimes drunk or used for cooking and hygiene without any treatment. Firewood and natural gas were used as fuel to treat approximately 5 litres of drinking water per day. Domestic water was stored in plastic containers, pots, concrete and plastic tanks, evidencing their vulnerability to water supply, especially in Mexico, presenting larger volumes of stored water at the household level (up to 1000 L, as observations during field visits). It is widely recognized that users require and demand continuing support after the technology implementation (Kayser et al., 2014; Foster, 2013; Mandara et al., 2013). In this regard, delivering training on the HWTS operation and maintenance was key towards ensuring its long-term sustainability. Furthermore, this intervention prioritised elements such as the local availability and affordability of replacements, as well as qualified persons in the community to perform more demanding maintenance tasks when required (local community technicians) (Wedgworth et al., 2014). These became even more relevant after the intervention.

The HWTS systems were installed and maintained by the communities with some technical support from Cantaro Azul in Mexico, and by the project team in Colombia. In Colombia, the routine maintenance of the HWTS systems was made by the users after prior training, which permitted establishing a relationship of ownership and caring for the systems by the communities. In Mexico, four community volunteers were trained to deliver basic maintenance to the HWTS systems in the long term. These volunteers acted in coordination with community leaders to guarantee adequate maintenance. Cantaro Azul (the NGO responsible for the installation of the HWTS systems in the field) continued to follow and strengthen this strategy within the communities. Both strategies were adapted to the specific contexts of each community to guarantee the long-term sustainability of the systems in terms of their use and basic maintenance. Our observations in the field confirmed that this approach was well accepted by the community members and that the systems were functional and with acceptable conditions of hygiene for at least the 12 months of duration of this field study.

Additionally, the main challenges identified in the field of providing safe drinking water to rural and isolated communities of developing countries are identified and discussed. The reader should appreciate that this was a field trial of systems in real communities of Colombia and Mexico. There were many challenges to overcome, including the COVID pandemic. Some data may not be complete or as detailed as we would like. Nevertheless, this paper presents a comprehensive study of a drinking water intervention under real conditions focusing on water treatment and quality.

3.1.1. Community parameters

The social tools used with the communities were workshops, interviews, and training for system users. The community workshops worked on several water-related aspects, including water quality (physical, chemical, and microbiological) perception and water uses by the communities, the risks of consuming untreated water, and existing treatment systems. These workshops aimed to create awareness and motivate the communities to understand and learn about water aspects in their daily lives, including domestic uses, water fetching and water-health related issues. This led to the introduction of the research project and the details of the intervention later. One-to-one interviews were carried out between field researchers (social scientists) and family' members to understand the community's water vision and how they would interact with the new technology. In all cases, housewives (also mothers), who spend more time in their homes, received training on the operation and use of the system. The community training activities consisted of basic cleaning and maintenance of the HWTSs. This was initially delivered to all households affected by the intervention by the project team and subsequently by the users to other family members. For technology maintenance, a group of community volunteers and local technicians were trained to provide basic guidance to end-users on the operation and maintenance of the installed HWTSs. Finally, they were provided with the system maintenance manual, basic tools, and filters necessary to perform this activity (Supplementary materials, Figure S.6).

3.2. Raw water quality

Raw water samples met the requirements of pH and conductivity according to the national and WHO drinking water guidelines (Colombian Government, 2007; Mexican Government, 2021; WHO, 2024). Concerning turbidity, raw water was complying with norm values in Mexico (max. 4 NTU) and the WHO (max. 5 NTU), but not in Colombia (max. 2 NTU). The microbiological parameters were above the maximum permitted (non-detectable CFU/MPN per 100 mL) by the drinking water regulations (Table 1).

3.3. HWTS efficiency in the field

3.3.1. Physicochemical results

Turbidity values in Chimix (1.2 ± 1.4 NTU) were quite low compared to both Colombian communities (El Carmelo: 6.1 ± 15.1 NTU, Curití: 29.5 ± 63.9 NTU). This can be attributed to the way the water is fetched and carried to the homes and the HWTSs. In Mexico, the water is not piped; households are typically supplied from small springs, which are naturally filtered. Only in the case of rainwater harvesting, very high turbidity values, over 100 NTU, were observed; then the raw water was pre-filtered (20 μm) before entering the sedimentation tank of the HWTSs. In Colombia, the households were supplied by untreated piped water, which generally had more suspended solids due to the heavy pumping in place. The turbidity of the raw water in El Carmelo (0.35–159.0 NTU) and Curití (0.70–594.3 NTU) presented great variability due to seasonal and climate changes. Colombia has bimodal rain cycles, which means that in rainy periods, high turbidity peaks are reached. In addition, there are problems of unprotected water sources associated with the lack of water and waste management of livestock farming and agriculture. Turbidity control could present a challenge by reducing the effectiveness of UV disinfection, increasing the potential risk for microbial contamination, and creating the need for more frequent filter cartridge replacements (Baldasso et al., 2021; Falcone et al., 2023). Comprehensive information on the turbidity, UVT_{254}, *E. coli* and TC for each household, including the number of samples collected, is detailed in the Supplementary Materials (Tables S.2 and S.3), which is summarised in Table 2 for turbidity and UVT_{254}. No changes in temperature, pH and conductivity were found in the water-treated tank (SP3) compared with the untreated water samples (SP1).

Turbidity removal between the raw water tank (SP1) and the treated water tank (SP3), during the 12 months of evaluation, ranged between 33 (± 79) % in El Carmelo and 78 (± 36) % in Curití, with significant differences ($p < 0.001$, Mann-Whitney test). In Chimix, the removal was 22 (± 106) %, also presenting significant differences ($p < 0.001$, Mann-Whitney test). These values were below the recommended turbidity threshold by the WHO (< 5 NTU) (WHO, 2024) in 97.7 % (167 of 171) of the samples in El Carmelo, in 98.8 % (394 of 399) in Curití and 98.9 % (189 of 191) in Chimix. The house tap samples showed a slight increase in turbidity attributed to the distribution systems in the home. Turbidity remained below the levels recommended by the WHO in almost all samples in El Carmelo 98.6 % (158 of 160) in the kitchen taps and 95.6 % (44 of 46) in the bathroom taps, while in Curití 97.8 % (358 of 366) in the kitchen and 95.8 % (162 of 169) in the bathroom (Table S4). The turbidity at the Chimix taps was not assessed.

We observed that the water after treatment (SP3) in El Carmelo and Curití had very similar UVT_{254} values (Table 2). For Chimix, the UVT_{254} slightly decreases from 91.9 (± 18.0) % before the treatment to 87.6 after the treatment (± 28.9) %. This parameter is not contemplated in the drinking water guidelines, but it is very influential on the efficacy of the UV disinfection systems. We measured before and after to determine this value after filtration and understand the disinfection rates observed.

The water optical properties are key to interpreting the UV disinfection performance of the water treatment systems in the presence of natural dissolved matter (natural organic matter-NOM- and/or humic acids -HA-) and suspended inorganic matter (turbidity). UVC transmittance at 254 nm is directly affected by the presence of light-absorbing compounds, including NOM, usually dissolved, among other chemicals. Baldasso et al. (2021) reported a UV disinfection model that elucidated the detrimental effect of very low concentrations of humic acids, reducing the UV inactivation rate of MS2 bacteriophage by 40 % for 3.5 mg/L of HA (UVT_{254} ranged between 77 % and 80 %). For water samples with UVT_{254} values of 85 % and above, the performance reduction was much lower, while they reported a non-significant effect of turbidity values lower than 5 NTU and a lack of synergistic effects between both parameters at these levels (Baldasso et al., 2021). The turbidity and UVT_{254} values for this study (Table 2) show that the working conditions might not represent a strong barrier to UV disinfection. The UV disinfection system flow rate (3 L/min) was set to deliver the UV dose for a 5-log reduction in MS2 bacteriophage, a UV-resistant viral surrogate for pathogenic virus disinfection, requiring a much higher UV dose than bacteria and protozoa (Hull and Linden et al., 2018).

Table 1
Water quality parameters for raw water samples in the three communities.

	El Carmelo	Curití	Chimix
pH	7.2 ± 0.7	8.2 ± 0.6	7.5 ± 1.0
(N)	(*N* = 173)	(*N* = 400)	(*N* = 213)
Conductivity (μS/cm)	29.7 ± 19.9	119.0 ± 40.1	524.6 ± 405.0
(N)	(*N* = 173)	(*N* = 400)	(*N* = 213)
Turbidity (NTU)	6.1 ± 15.1	29.5 ± 63.9	1.2 ± 1.4
(N)	(*N* = 173)	(*N* = 399)	(*N* = 213)
(Min - Max)	(0.4 – 159.0)	(0.7 – 594.3)	(0.2 – 11.3)
Temperature (°C)	21.1 ± 3.2	24.3 ± 3.1	16.0 ± 1.1
(N)	(*N* = 173)	(*N* = 400)	(*N* = 213)
(Min - Max)	(15.2 – 25.6)	(16.3 – 26.2)	(14.5 – 18.9)
UVT_{254} (%)	91.8 ± 7.0	86.4 ± 11.7	91.9 ± 12.5
(N)	(*N* = 173)	(*N* = 400)	(*N* = 212)
(Min - Max)	(62.2 – 100.0)	(24.0 – 99.6)	(16.5–100.0)
E. coli (CFU or MPN/100 mL)	103 ± 364	228 ± 916	28 ± 35
(N)	(*N* = 173)	(*N* = 400)	(*N* = 212)
(Min - Max)	(DL – 4 × 10^3)*	(DL – 1 × 10^4)*	(DL – 100)**
TC (CFU or MPN/100 mL)	(3 ± 16) × 10^3	(4 ± 17) × 10^3	76 ± 39
(N)	(*N* = 173)	(*N* = 401)	(*N* = 212)
(Min - Max)	(DL – 2 × 10^6)*	(DL – 2 × 10^6)*	(DL – 100)**

N is the number of samples. UVT_{254} is sample transmittance measured at 254 nm.
DL = detection limit = 1 CFU/100 mL (El Carmelo, Curití) 1 MPN/100 mL (Chimix).
* CFU/100 mL. ** MPN/100 mL TC = Total Coliforms numbers.

Table 2
Turbidity and UVT_{254} before (SP1) and after treatment (SP3).

	Colombia		Mexico
Parameter	El Carmelo	Curití	Chimix
Turbidity (NTU) before	6.1 ± 15.1	29.5 ± 63.9	1.2 ± 1.4
(Min – Max)	(0.4 – 159.0)	(0.7 – 594.3)	(0.2 – 11.3)
Turbidity (NTU) after	1.4 ± 1.1	1.3 ± 0.9	0.7 ± 0.9
(Min – Max)	(0.5 – 7.2)	(0.4 – 29.0)	(0.0 – 8.2)
UVT_{254} (%) before	91.8 ± 7.0	86.4 ± 11.7	91.9 ± 12.5
(Min – Max)	(62.2 – 100.0)	(24.0 – 99.6)	(16.5–100.0)
UVT_{254} (%) after	93.2 ± 7.4	93.4 ± 3.8	87.6 ± 25.0
(Min – Max)	(31.4 – 100.0)	(71.2 – 100.0)	(0.0 – 100.0)

3.3.2. Microbiological results

All systems were able to reduce *E. coli* to potable levels, i.e. below DL, in most samples, regardless of raw water initial values (Fig. 3a). Data from El Carmelo showed initially 103 (±364) CFU/100 mL in the raw water, which was reduced to 1 (±5) CFU/100 mL, on average following treatment, while in Curití the treatment reduced the *E. coli* from 228 (± 916) to 5 (± 36) CFU/100 mL. No statistical difference between the communities concerning the *E. coli* counts after treatment ($p = 0.066$, Mann -Whitney test) was observed. In El Carmelo, only 17 water samples out of 171 (10.0 %) were failures for potable quality (i.e. didn't meet the potable quality microbial standards for *E. coli*), while in Curití, there were 56 failures out of 399 (14.0 %) (Fig. 3a). In Chimix, the *E. coli* numbers in the raw water samples were on average 28 (± 35) MPN/100 mL, which was reduced to 5 (± 18) MPN/100 mL following treatment. In Chimix, 17 out of 82 samples (20.7 %) indicated failures.

The TC count was initially much higher in all samples (Fig. 3b). In El Carmelo TC was reduced from 2990 (± 15,800) to 326 (± 2110) CFU/ 100 mL, and from 4080 (± 17,100) to 425 (± 3310) CFU/100 mL in Curití, with significant differences between treated water samples ($p < 0.001$, Mann-Whitney test). According to the Colombian and Mexican guidelines for drinking water quality, TC must be equal to 0 CFU/100 mL. In Chimix the TC numbers in raw water dropped from 76 (± 39) MPN/100 mL to 14 (± 32) MPN/100 mL.

3.3.2.1. Statistical analysis and correlations of microbial results. The bivariate analysis permitted the determination of potential correlations between all measured variables (turbidity, UVT_{254}, *E. coli*, TC, cumulative treated volume, frequency of changing the controllers, filters, lamps, pumps and tanks). In El Carmelo, the *E. coli* numbers in the treated water tank (SP3) had a weak and positive correlation with the raw water turbidity ($p = 0.059$, $|r| = 0.126$), and a weak and negative correlation with the systems operating time ($p = 0.064$, $|r| = - 0.142$). All the other evaluated parameters, i.e. UVT_{254}, *E. coli,* TC of the raw water, cumulative treated volume, and frequency of changing the control boxes and filter cartridges, did not correlate with the *E. coli* values at the SP3 sampling point. As expected, the data from Curití showed that *E. coli* values in SP3 correlated strongly and positively with TC ($p = 0.015$, $|r| = 0.122$) and with cumulative treated volume ($p = 0.050$, $|r| = 0.098$). This strong correlation is attributed to the fact that TC and *E. coli* counts are both related to the microbiological water quality, which in this case is, on average, much higher than in El Carmelo, as the water quality in El Carmelo is in general better than in Curití (Table 1). The filters were visibly deteriorated when replaced every 3–4 months. This was visible in Curití (max. value of treated water recorded of 137.6 m^3 per month), where the treated water volumes were significantly higher due to the COVID pandemic and increased hygiene needs. Afkhami et al. (2021) showed that for pleated filters, turbidity efficiency removal improved over time as the treated volume increased (>0.9–1.2 m^3). Individual analyses of each household indicated that 50 of the 52 treatment systems installed in Colombia (Fig. 4a) were efficient in reducing *E. coli* ($p < 0.05$, Wilcoxon and paired *t*-tests) to produce potable water, and 46 of the 52 delivered water-free from *E. coli,* i.e. treated water with *E. coli* levels below the DL ($p < 0.05$, Wilcoxon and paired *t*-tests). In Mexico, 11 out of 20 were efficient in reducing *E. coli* to potable levels (Fig. 4b). These results confirmed the greater probability of recontamination of treated water in Mexican households.

3.4. Household tap recontamination

3.4.1. E. coli recontamination

In El Carmelo the average values of *E. coli* in the treated water tank (SP3), in the kitchen tap (SP4) and in the bathroom tap (SP5) were lower than the values found in Curití (Table 3, Fig. 5a). In both communities, there was a slight increase in *E. coli* values in the kitchen and bathroom taps compared to the treated water tank. However, this recontamination caused by the distribution of water into the homes was not statistically significant for SP3 ($p > 0.05$, Wilcoxon and paired *t*-tests). Despite these results, the absence of *E. coli* (below DL) was maintained in 83.7 % (134 of 160) of the SP4 samples and 93.6 % (44 of 47) of the SP5 samples in El Carmelo. In Curití, *E. coli* was absent in 94.2 % of the samples (343 of 364) of SP4 and in 82.2 % (139 of 169) of SP5. In Chimix, no regrowth of *E. coli* was evident during water distribution in homes with values below the detection limit (BDL) in SP4 and 4 ± 15 MPN/100 mL in SP5 (Table 3, Fig. 5a). The absence of *E. coli* was maintained in 93 % (114 of 123) of SP4.

3.4.2. TC recontamination

In Curití and El Carmelo, the water available in SP4 (kitchen tap) was the most susceptible to TC recontamination. For El Carmelo, the average TC numbers in SP4 and in SP5 (bathroom tap) were lower than the values found in Curití (Table 3, Fig. 5b). In El Carmelo, the absence of TC was maintained in 27.5 % (44 of 160) of the SP4 samples and in 52.2 % (24 of 46) of the SP5. While in Curití, this absence was reduced to 19 % (70 of 367) of the SP4 samples and 17.6 % (30 of 170) of the SP5. As shown in Fig. 5b, in El Carmelo there was an increase in TC counts of 0.26 (± 0.30) log in SP4 and 0.22 (± 0.31) log in SP5 versus SP3, while in Curití this increase was 0.19 (± 0.28) log and 0.23 (± 0.45) log for SP4 and SP5, respectively. No significant differences in TC recontamination were observed in SP4 ($p > 0.109$, Wilcoxon test) and SP5 ($p > 0.066$, Wilcoxon test), indicating that both communities have the same

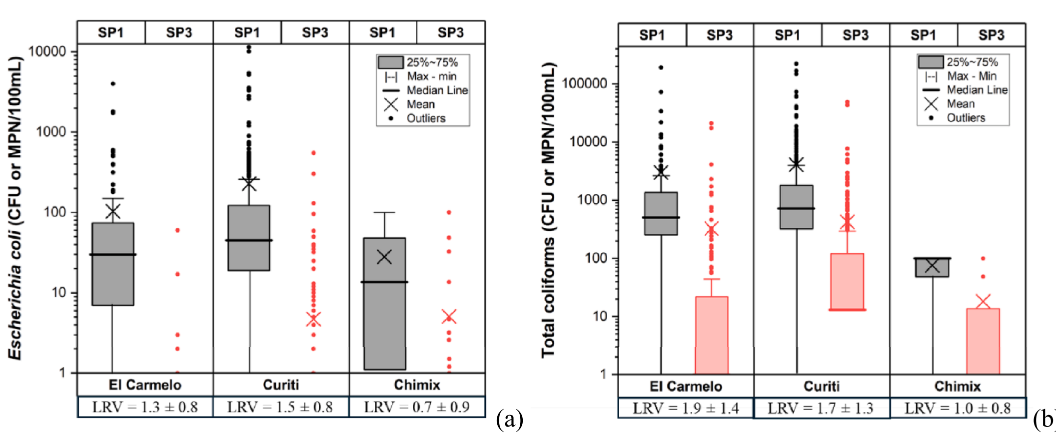

Fig. 3. Box-plot graphs of log-*E. coli* (a) and log-total coliforms (b) counts in raw water (SP1-black symbols) and treated water (SP3-red symbols) corresponding to the HWTSs in El Carmelo, Curití, and Chimix. The LRV row at the bottom indicates the average log-reduction value for each community. Detection limit of 1 CFU/100 mL for El Carmelo and Curití, and 1 MPN/100 mL for Chimix. Samples below the DL are not shown.

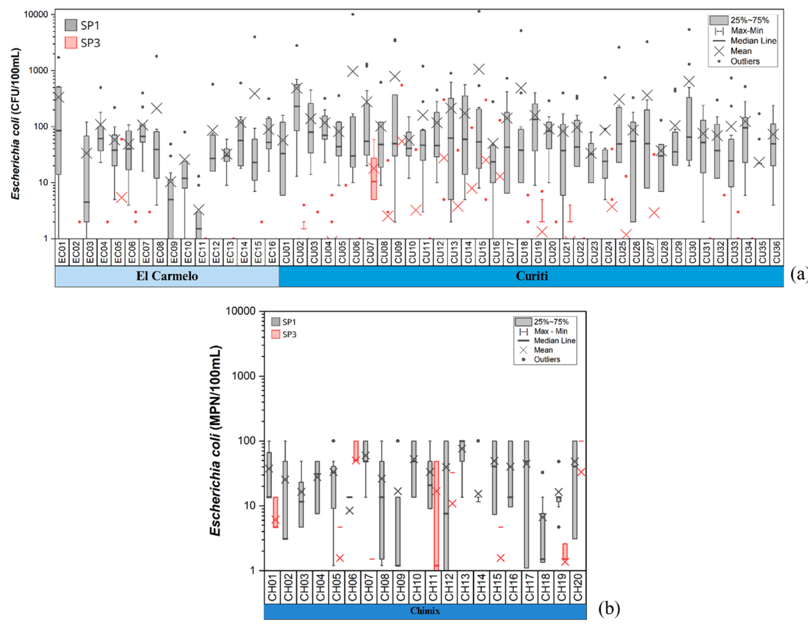

Fig. 4. Box-plot graphs of *E. coli* log-count in raw (SP1) and treated water (SP3) for 12 months. Comparison of 16 HWTSs in El Carmelo and 36 HWTSs in Curití (a), and 20 HWTSs in Chimix (b). Detection limit of 1 CFU/100 mL for El Carmelo and Curití, and 1 MPN/100 mL for Chimix.

Table 3
E. coli and total coliforms in treated water tank (SP3), kitchen tap (SP4) and bathroom tap (SP5).

		El Carmelo	Curití	Chimix
E. coli (CFU or NMP/100 mL)	SP3	1 ± 5*	5 ± 36*	5 ± 18**
	SP4	2 ± 6*	13 ± 134*	< DL**
	SP5	1 ± 3*	8 ± 66*	4 ± 15**
Total coliforms (CFU or NMP/100 mL)	SP3	326 ± 2109*	425 ± 3313*	18 ± 34**
	SP4	267 ± 1115*	835 ± 10,829*	42 ± 44**
	SP5	180 ± 530*	424 ± 2925*	42 ± 44**

* CFU/100 mL. ** MPN/100 mL.

possibility of TC regrowth during the distribution of water in homes. In Chimix there was a significant increase in TC values in SP4 and SP5 ($p < 0.001$, Mann-Whitney test). Mean TC values increased from 18 (± 34) MPN/100 mL in SP3 to 42 (± 44) MPN/100 mL in SP4 and 42 (± 44) MPN/100 mL in SP5. Total recontamination by TC in SP4 and SP5 was 0.50 (± 0.98) log and 0.65 (± 0.97) log, respectively. Water with 100 MPN/100 mL TC was found in 34 % (65 of 191) of the samples taken in SP4 and in 33 % (23 of 70) of those from SP5. In the case of TC, cleaning the taps reduced TC values to 23 (± 36) MPN/100 mL in SP4, however, it was not enough to improve water quality. The presence of TC in the water samples analysed from SP4 and SP5 in the three communities evidenced the existing contamination within the house distribution system in the homes due to the presence of TC after the treatment in most cases (Fig. 5b).

Some countries, like Colombia and Brazil, include TC levels as zero in standards for potable water in centralized drinking water systems, although obviously these standards are not applied to the communities we studied. The water quality was compatible with the WHO recommendation in most samples; only a few samples showed high values of *E. coli* in SP4 (2×10^3 CFU/100 mL) of the 'CU14' house and in SP5 (8×10^2 CFU/100 mL) of the 'CU22' house, both in Curití. The microbiological quality of water can be affected by the storage, the hygienic status of the taps, and by the distribution network inside the home, which may lead to biofilm formation and act as a source of contamination. Some authors suggested that long-term water storage could lead to benthic growth of bacteria in sediments and/or biofilms on the walls of tanks and pipes (Liu et al., 2014; van der Wielen et al., 2016). Thus, these values could have been generated as a product of the detachment of colonies that grew on the biofilms that form in the distribution pipes since these waters are not chlorinated.

It is accepted that the presence of biofilms in drinking water distribution systems is responsible for water quality deterioration and is a

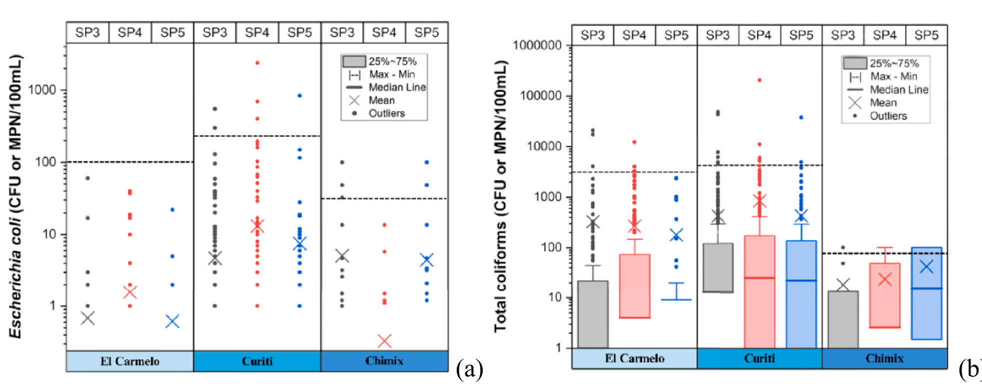

Fig. 5. Box-plot graphs of the *E. coli* (a) and total coliforms (b) log-count in the treated water tank (SP3), kitchen (SP4) and bathroom (SP5) taps corresponding to the HWTSs in El Carmelo, Curití, and Chimix. DL: 1 CFU/100 mL (El Carmelo and Curití), 1 MPN/100 mL (Chimix). Dashed lines indicate raw water tank values (SP1).

possible source of public health risks (Oliveira et al., 2024). The use of common disinfectants (chlorine and chloramine) controls the microbial communities within biofilms. Other strategies based on multi-barrier processes that combine disinfection with other water treatment methods, such as filtration, improve the control of opportunistic pathogens, reduce the chlorine-tolerance of biofilm-embedded cells, and decrease the corrosion rate in metal-based pipelines (Oliveira et al., 2024). Our findings demonstrate the importance of cleaning tanks and pipes to avoid recontamination at the point of use. This is consistent with Liu et al. (2016), who confirmed that the presence of pathogens and biofilms during water storage can be reduced by cleaning tanks using disinfecting solution and shortening storage to reduce biofilm proliferation (Liu et al., 2016; USEPA, 2002).

Our results clearly show that microbial recontamination in taps is quite frequent and can become an issue for water security inside homes. Only chlorination and combined flocculation/disinfection provide a residual disinfectant necessary to protect the water quality during storage (Clasen et al., 2007). Therefore, using additional chlorination to maintain a residual level of disinfection as a final stage to avoid recontamination inside the houses is recommended. Lindmark et al. (2022) proposed that the deployment and management of passive chlorinators at scale can enhance the quality of existing accessible and available water services to meet "safely managed" requirements (Lindmark et al., 2022). Adding chlorinators to the HWTS systems would increase the intervention costs. Consequently, a deeper study on residual disinfection delivery at a minimum cost would be advisable and strongly desirable. However, in many cases chlorinated water is not acceptable to the communities, and it may not be adopted, unless carefully controlled to avoid taste and odour problems.

3.5. Water health risk analysis

Raw water samples showed *E.coli* levels correlating to moderate to very high health risk (between 1 and >100 CFU-MPN/100 mL) in 91 % of the samples in El Carmelo, 95 % in Curití, and 77 % in Chimix. This falls within the range of health risks identified in LMICs because of poor drinking water quality, i.e. low risk for numbers between 0 (or below DL) and 1; moderate risk from 1 to 10; high risk between 10 and 100; and very high risk for counts >100 (WHO, 2024; Khan et al., 2022). After treating the water with the HWTSs, these values decreased to 10 % (17 of 171) in El Carmelo, 14 % (56 of 399) in Curiti, and 21 % (17 of 82) in Chimix (Fig. 6). The percentage of houses with high-risk levels when sampled inside (at the kitchen and bathroom taps) was like those above. The WHO health risk index is based solely on *E. coli* numbers; therefore, TC values are not considered. These results highlight the positive impact of the treatment technology on health risk. Previous research analysed the WHO risk level of treated water after different interventions using different HWT methods in the field. For example, for a HWTS intervention based on household filtration in Rwanda, the proportion of samples with low risk increases 2.4 times to the untreated water samples (n = 929) (Haque et al., 2022). For bio sand filters as a point of use technology in a field study in the Dominican Republic, the reduction in the number of samples with low risk after treatment was from 68 to 19 (n = 170) (Aiken et al., 2011). Reygadas et al. (2015) evaluated the efficacy and risk of an ultraviolet disinfection and safe storage system in rural communities in Mexico, finding that the proportion of samples with low risk were a 75 % (n = 624), compared with the 36 % of untreated samples (n = 1781) (Reygadas et al., 2015).

3.6. Cost analysis of safewater HWTSs

Table 4 displays the initial investment (updated to Dec 2024) for a single HWTS in Colombia (USD 1470.8) and Mexico (USD 1470.8) prototype, as well as the breakdown cost for each component. The biggest expenses included the metal structure, pipes, fittings, valves, accessories, pump, control box, electrical connections, UVC reactor and labour. Maciel et al. (2021) obtained similar costs (i.e. USD 1114 on January 2021 or USD 1424.9 updated to March 2024) in a HWTS in Brazil, with a daily production of 180 L, and pretreatment and chlorination as additional treatment. These costs apply to the prototype systems installed as part of the SAFEWATER project and scaling up to larger numbers would result in significant cost savings.

The actual usage of water in Colombia was on average 54–60 L day^{-1} but there was significant variation between households. The average number of persons per household in Colombia was 4.7 meaning that consumption was only ca. 13 L per person per day (data not available for Mexico). Given the variation, the annual operation and maintenance costs were estimated based upon providing 150 L per day which was the volume the systems were designed to deliver in one cycle, and this would represent maximum consumption reported. The O&M costs are mainly fixed, relating to labour in cleaning and replacement of filters, and not so sensitive to the volume of water treated (if ≤150 L per day).

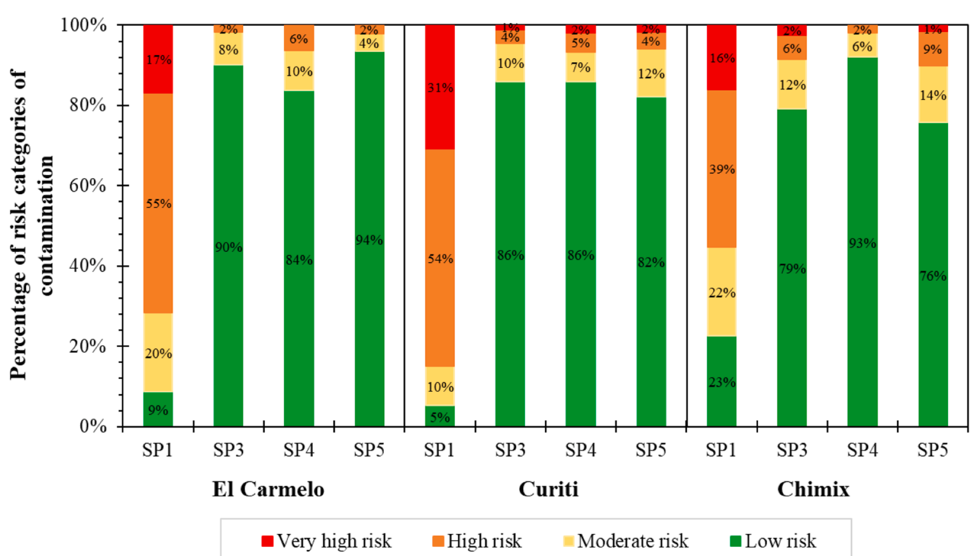

Fig. 6. Health risk levels for household samples in the rural communities of El Carmelo, Curití and Chimix. DL: 1 CFU/100 mL (El Carmelo and Curití), 1 MPN/100 mL (Chimix). Low risk for counts between 0 (or below DL) and 1; moderate risk from 1 to 10; high risk between 10 and 100; and very high risk for counts >100 (WHO, 2024).

Table 4
Costs of HWTSs and treated water in Colombia and Mexico.

	Colombia	Mexico
System Installation costs (USD)		
Metal structure	395.2	303.4
Pipes, fittings, valves and accessories	205.6	211.8
Enclosure box and Electrical Connections	197.8	129.8
Labor	178.8	163.8
UVC reactor	137.0	129.5
Diaphragm pump	106.8	169.2
Water tanks[1]	86.9	142.2
Automatic system control[2]	84.3	99.0
Filter housings	40.9	61.3
Filters	15.3	16.6
Other costs (e.g. concrete base)	22.4	11.1
Total investment cost	**1470.8**	**1437.7**
Annual Operation and Maintenance costs (USD)		
Electricity consumption[3]	7.2	4.0
Filters and UV lamp replacement[4]	46.5	50.2
Labour costs[5]	133.32	170.4
Total	**187.02**	**224.6**
Cost of treating one litre of water		
Daily water production (L)	150	150
Annual water production (L)	54,750	54,750
Basic Cost of treated water considering only operation and maintenance costs (USD cents/L)	**0.34**	**0.41**
Total Cost of treated water including initial investment and O&M costs (USD cents/L)	0.61	0.67

[1] Water tanks in Colombia (150 L) and Mexico (250 L).
[2] Imported automatic control (made in the UK).
[3] Cost of electric consumption of the controller, pump and UV lamp.
[4] Filter change every three months.
[5] One day per month is estimated to be required and costed at basic salary wages in Colombia (11.11 USD day^{-1}) and Mexico (14.20 USD day^{-1}):.

Costs are higher for Mexico ($ 224.6 USD) as compared to Colombia ($187 USD). Labour costs were highest, but these may not be an actual charge if the communities clean the systems and replace the filters themselves, however, it highlights the commitment and effort required in maintaining the systems. Filter replacement was the highest cost after labour, which is consistent with the findings of Maciel et al. (2021). The cost of treated water was estimated to be less than one cent per litre for both countries even when considering the initial investment cost (depreciated over 10 years, Table 3). However, finding that initial investment would be challenging and is beyond the capacity of the communities. In Colombia, 16 % of the population were living on less than $3.2 USD per day in 2022, and in Mexico, 7.1 % of the population were living in extreme poverty, i.e. less than $2.15 USD per day. Even where the cost of water is <1 cent per litre, it still may exceed 3 % of the household annual income, which is the estimated maximum that people should pay for water (Watkins, 2006). This is crucial for those living in unplanned settlements where the cost might be 5 to 10 times higher than in high-income zones (OHCHR, 2010). In LMICs, access to a safe drinking water source could pose a significant financial burden due to lower incomes. In this situation, many families are forced to use contaminated water sources, compromising their health and dignity in the process. After analysing the costs obtained, the concept of low-cost technologies must be rethought as it traditionally applies to HWTSs with low water production, for example, < 20 L per day for a single family. Providing larger volumes of treated water represents higher costs. For example, a Brazilian HWTSs including slow sand filtration and a UVC disinfection producing 48 L/day costs $USD 718.29 (de Melo Neto et al., 2024). The lowest cost for HWTSs has been reported for household chlorination and solar disinfection, with estimated costs of about 0.66 USD and 0.63 USD per disability-adjusted life year (DALY), respectively (Clasen et al., 2007). Our intervention, using automated water treatment systems with UVC disinfection, was able to provide safe potable water, acceptable to the communities, in sufficient amounts, accessible in the homes (although tanks need to be filled in Mexico), but not affordable to the poor in marginalised communities without support on the initial investment.

4. Conclusions

Regardless of the initial raw water quality, HWTSs proved to be efficient in inactivating *E. coli*, reducing the average counts to potable levels below the detection limit, and generating safe water to be delivered to families in rural communities that lack treatment systems. Most proposed solutions usually fail to provide sufficient water for the daily demands for a typical household in LMICs, which must be safe and of acceptable quality at the crucial home consumption points, not only for drinking but also for hygiene and cooking. This study showed the importance of cleaning and hygiene of the water treatment systems within domestic settings to prevent water recontamination in home taps, which could be prevented using additional low-cost chlorination to maintain a residual disinfection, if acceptable to the communities. The high counts of *E coli* found in raw waters demonstrated the health risk posed in rural communities and the positive impact that HWTSs had in reducing microbiological risk. Social appropriation in the operation, maintenance and cleaning of HWTSs is essential to guarantee their correct functioning and prevent the growth of microorganisms in the treated water tank and distribution network. These field trials have demonstrated that UVC water treatment can improve, from 12 to 85 % the availability of safe drinking water (<1CFU-MPN/100 mL) in the communities, reducing the health risk. However, the capital expenditure for the installation of such systems is high and a consistent effort or cost is required in the maintenance of the systems. Our intervention, using automated water treatment systems with UVC disinfection, was able to provide safe potable water, acceptable to the communities, in sufficient amounts, accessible in the homes (although tanks need to be filled in Mexico), but not affordable to the poor in marginalised communities without support on the initial investment.

Research data for this article

Raw data of water quality monitoring used to elaborate this article are available in the following links (Link Colombia, Link Mexico), which are available upon request to the corresponding author. The Supplementary Materials section shows the detailed analysis of curated data and extra information about the cost analysis.

CRediT authorship contribution statement

M. Hincapié: Writing – original draft, Resources, Methodology, Conceptualization. **A. Galdós-Balzategui:** Writing – review & editing, Methodology, Investigation, Conceptualization. **B.L.S. Freitas:** Writing – original draft, Data curation. **F. Reygadas:** Funding acquisition, Conceptualization. **L.P. Sabogal-Paz:** Writing – original draft, Formal analysis, Data curation. **N. Pichel:** Writing – original draft, Methodology, Investigation. **L. Botero:** Writing – review & editing, Writing – original draft, Methodology. **L.J. Montoya:** Writing – review & editing, Methodology, Investigation. **L. Galeano:** Writing – review & editing, Methodology, Investigation. **G. Carvajal:** Writing – review & editing, Methodology, Investigation. **H. Lubarsky:** Methodology, Investigation. **K.Y. Ng:** Writing – review & editing, Software, Investigation. **R. Price:** Writing – review & editing, Supervision, Methodology, Conceptualization. **S. Gaihre:** Writing – review & editing, Methodology, Conceptualization. **J.A. Byrne:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **P. Fernández-Ibáñez:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: John Anthony Byrne reports financial support was provided by Engineering and Physical Sciences Research Council. Pilar Fernandez-Ibanez reports financial support was provided by The Royal Society. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2025.123888.

Data availability

Data will be made available on request.

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