International Journal of Hygiene and Environmental Health 244 (2022) 114004

Contents lists available at ScienceDirect

International Journal of Hygiene and Environmental Health

journal homepage: www.elsevier.com/locate/ijheh

Chlorination for low-cost household water disinfection – A critical review and status in three Latin American countries

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ARTICLE INFO

Keywords:
Chlorination
Household water treatment
Water disinfection
Drinking water
Rural households

ABSTRACT

Chlorination has historically provided microbiologically safe drinking water in public water supplies. Likewise, chlorine has also been introduced as a low-cost disinfection method in rural and marginalized communities, both at community and household level, as well as during emergencies. Although this practice is common and well established for use as a household water treatment technology in the Global South, several challenges in effective and efficient implementation still need to be addressed. Here, we explored these issues by a literature review and narrowed them to the status of three Latin American countries (Mexico, Colombia, and Brazil). Overall, it was found that although guidance on household-based chlorination includes information on health risks and hygiene, this may not create enough incentive for the user to adapt the method satisfactorily. Physicochemical quality of the water influences chlorination efficiency and it is found that variations in quality are rarely considered when recommending chlorine doses during implementation. These are far more often based on a few measurements of turbidity, thereby not considering dissolved organic matter, or seasonal and day-to-day variations. Other factors such as user preferences, chlorine product quality and availability also represent potential barriers to the sustainable use of chlorination. For chlorination to become a sustainable household water treatment, more focus should therefore be given to local conditions prior to the intervention, as well as support and maintenance of behavioural changes during and after the intervention.

1. Introduction

Access to sufficient, safe, acceptable, and affordable water is considered as a human right and is an integral part of the sustainable development goals formulated by the United Nations (WHO and UNICEF, 2017). Although there has been an increasing focus on realising this human right, it remains that 2.1 billion people did not have access to safely managed drinking water in 2020. Instead, they rely on water sources, which are prone to contamination and/or located far from the households (WHO and UNICEF, 2020; WHO, 2021). Consumption of unsafe drinking water can cause significant health problems and mortality from enteric infections, particularly among children (Nguyen et al., 2021). Some of the most prevalent causes of mortality due to diarrhoeal diseases are pathogens such as rotavirus, *Cryptosporidium*, and *Salmonella* (GBD, 2018). They are mainly transmitted through the faecal-oral route and are associated with unsafe drinking water, poor sanitation, and hygiene (Clasen et al., 2007).

Household water treatments (HWTs), where water is treated at the point of use, can be an important solution to help mitigate these problems, especially when centralised solutions are not feasible due to e.g. the high cost, maintenance requirement, or where the households are not located in clusters. Although many different technologies exist that have the potential to provide safe drinking water, they are challenged by

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https://doi.org/10.1016/j.ijheh.2022.114004
Received 11 February 2022; Received in revised form 21 May 2022; Accepted 26 June 2022
Available online 8 July 2022

Abbreviations

AC	activated carbon
DBPs	disinfection by-products
CD	chlorine demand
CDC	centre for diseases control
CBHI	community-based health insurance
CHWs	community health workers
COFEPRIS	Federal Commission for Protection against Health Risks
DRC	Democratic Republic of Congo
E. coli	*Escherichia coli*
FC	free Chlorine
FRC	free residual chlorine
HAAs	haloacetic acids
HH	households
HWT	household water treatment
HWTS	Household water treatment and storage
INEGI	Instituto Nacional de Estadística, Geografía e Informática (Mexico)
LRV	log reduction value
NGO	non-governmental organisation
NOM	natural organic matter
PSI	Population Service International
RAS	Reglamento Técnico para el Sector de Agua Potable y Saneamiento Básico (Colombia)
SS	safe storage
SWS	Safe Water System
TC	total coliforms
THMs	trihalomethanes
TOC	total organic carbon
TTC	thermotolerant coliforms
TTHM	total trihalomethanes
UNICEF	United Nations Children's Fund
USEPA	U.S. Environmental Protection Agency
WASEH	water, sanitation, and education for health
WASH	water sanitation and hygiene
WHO	World Health Organisation
WS	water supply

a general low effectiveness and compliance under real conditions in the field (WHO, 2011). This represents an important gap in research since little is known about the actual circumstances under which the methods are performed.

Chlorine has been used as a disinfectant since the early 1900s (USEPA, 1999), and in the Global South, it is the most common and cost-effective method at household level compared to filtration, solar disinfection, and combined flocculation/disinfection. Of these methods, only chlorination and combined flocculation/disinfection provides a residual disinfectant necessary to protect the water quality during storage in the households, where there is a risk of recontamination. Here, chlorination has the clear advantage over combined flocculation/disinfection in that it is cheaper and easier to perform (Clasen et al., 2007).

At the household level, chlorination can be easily achieved by adding a certain dosage of household bleach, sodium hypochlorite (NaOCl) solution, and is one of the most accessible methods, since NaOCl is produced and sold widely. An alternative to NaOCl is sodium dichloroisocyanurate (NaDCC) tablets ($NaCl_2(NOC)_3$), sodium dichloroisocyanurate, which have the advantages of being more stable during storage, safer, and more convenient (Clasen and Edmondson, 2006; Lantagne et al., 2011).

Chlorine when added to water in molecular or hypochlorite form undergoes hydrolysis to form aqueous molecular chlorine, hypochlorous acid and hypochlorite ion, which collectively are referred to as free chlorine (FC) (APHA et al., 2012). Both are antimicrobial agents, but HOCl is significantly more effective than OCl^- (Tvrdá and Benko, 2020). Free chlorine is effective against a range of bacteria and viruses associated with contaminated drinking water but it is less effective against protozoa, especially at the concentration range acceptable for drinking water (CDC, 2014a; Mohamed et al., 2015).

Although chlorination is a simple method for treating contaminated water, it faces several challenges for effective implementation, particularly in rural settings. The aim of this review is to deeply revise and critically analyse the scientific and grey literature on chlorination in practice to identify the main challenges and research gaps related to household chlorination in rural settings, the real scenarios for household chlorination, promotion and deployment, compliance, effectiveness and sustainability in the field. Special attention is put into the main barriers and enablers identified for adequate implementation in the Global South. For this, supported case studies from selected countries in Latin America, namely Mexico, Colombia, and Brazil have also been discussed.

2. Methodology

A literature review on household chlorination in rural settings in the Global South as well as supporting general technical information was performed. More than 3500 manuscripts were identified based on the search terms which were reviewed for inclusion of the relevant keywords and combinations of them by checking titles and abstracts. Peer reviewed literature was identified by searching electronic databases of Scopus, Web of Science, and Google Scholar using the keywords outlined in Table 1. Duplicate documents, review papers and publications in other languages than English, Spanish, and Portuguese were excluded. Research articles unrelated to chlorination in the Global South, to rural areas or purely based in lab studies were also excluded. Similar criteria were used for searching for grey literature. Additionally, some papers were found via reference chaining and information from the authors, who represent academics, researchers, and practitioners. Four hundred and eight articles were selected and the abstract (and method if necessary) were checked. The selected papers was reduced to 202 articles which were read in full length and studies were included in the final list if they were relevant to the topic.

3. Challenges with chlorination

3.1. Source water quality – dosing and storage

HWT systems must be robust in terms of their capability to treat water with variable microbial and physicochemical quality. When chlorine is added to water, it reacts with the organic material, metals, and other components, which render it unavailable for disinfection. The difference between the amount of added chlorine and the free residual

Table 1
Review search keywords, selecting the combination as ((‘chlorination method keyword’) AND (‘water treatment keyword) AND (‘setting keyword’).

Chlorination keyword	Water treatment keyword	Setting keyword
disinfect* chlorin* hypochlorite “sodium dichloroisocyanurate" NaDCC bleach	“drinking water” potable “water treat*" household HTW “household water treatment” “Safe water system" SWS “point-of-use” -POU	rural communit* “field trial” intervention “field implementation" “developing countr*" LMIC “low and middle income country"

chlorine (FRC) after a given contact time is defined as the chlorine demand (CD). This CD depends on various parameters such as temperature, pH, turbidity, and chemical composition of the water and the CD of a given water source is therefore prone to temporal variations (WHO, 2019). This underlines the importance of a more thorough knowledge of the water quality on a larger time scale. In terms of chlorination interventions, few studies, as in Boisson et al. (2013) and Ercumen et al. (2015), have conducted pilot studies to determine the optimal chlorine dose based on the relationship between water quality and CD. In some cases, the measured water quality parameters are limited to a few measurements of e.g. *Escherichia coli* (*E. coli)* concentration (Mengistie et al., 2013) or FRC (Ercumen et al., 2015); but in most cases, no information is given of the water quality and the dosage is typically based on the general recommendations of turbidity (Mohamed et al., 2015).

Many studies find a correlation between the turbidity and the CD of the water (Levy et al., 2014; Mclaughlin et al., 2009; Mohamed et al., 2015) and the latest recommendations by Wilhelm et al. (2018) for dosing, as seen in Table 2, are based on testing of a large range of water sources with varying turbidity values. The CD exerted by the turbidity is due to the reaction of chlorine with organic and inorganic compounds in the water, but since some of the natural organic matter present in water is dissolved and it is not reflected in the turbidity. This is rarely taken into consideration when deciding the chlorine dosage in an intervention.

It is recognised by the WHO that chlorine dosing should be site-specific due to the varying CD, and therefore their recommendations are based on the maintenance of FRC concentrations as listed in Table 2. From a health perspective, the WHO further recommends that FRC should not exceed 5.0 mg/L at any time (WHO, 2011).

The FRC concentrations of 0.2–0.5 mg/L are recommended to protect the water from regrowth and recontamination during storage and usage, however bacterial regrowth has been observed at the recommended FRC levels within this range. Meierhofer et al. (2019) found that safe, chlorinated water from a water kiosk with a mean FRC of 0.39 mg/L was not sufficient to maintain drinking water quality after 24 h of storage, when filled into uncleaned jerry cans and used in households in Kenyan households. The uncleaned jerry cans contributed to the exerted CD and reduced the FRC to a mean concentration of 0.19 mg/L. This fact provoked contamination at storage level, *E. coli* was detected in 15.2% of the household stored water after 24 h of storage and a higher chlorine dosage would have been required to maintain the FRC level in the water. This emphasizes the importance of using clean water storage containers to prevent depletion of FRC during storage.

3.2. Pathogens, dose and contact time

The efficiency of chlorination depends on dosage and contact time. A 4-log inactivation of most waterborne pathogens have been shown at a dosage of a few mg/L and a 30–60 min contact time. However, several pathogens exhibit resistance to chlorination, influencing the required chlorine concentration and contact time necessary for sufficient inactivation (Clasen and Edmondson, 2006). Pathogens like the protist *Cryptosporidium parvum*, for instance, are highly resistant to conventional chlorination due to the production of resistant oocysts during their life cycle (Feng et al., 2021). At the household level, under less controlled conditions than in a water treatment plant, studies such as Mclaughlin et al. (2009) and Levy et al. (2014) have found the efficiency to be significantly reduced compared to laboratory testing, which is attributed to low user compliance, recontamination during storage, or high CD leading to insufficient disinfection and regrowth.

Table 2
Recommendations for chlorine dosage and FRC for drinking water.

Applied dose/FRC	Concentration (mg/L)
Dosage at low turbidity (<10 NTU)	1.88 (Wilhelm et al., 2018)
Dosage at high turbidity (>10 NTU) (consumed within 8 h)	3.75 (Wilhelm et al., 2018)
FRC after 30 min	>0.50 (WHO, 2011)
FRC after 24 h	>0.20 (WHO, 2011)

Although chlorination is supported by leading organisations such as UNICEF (Mohamed et al., 2015), the ineffectiveness against some protozoa means that chlorination products can only obtain a limited protection ('1-star' classification) as reflected in the Household Water Treatment Evaluation Scheme by the WHO (WHO, 2011). On this basis, WHO recommends that chlorination is only used in situations where the causative pathogens for disease are known or as part of a multi-barrier treatment approach (WHO, 2019). This is the case of chlorine used for emergency responses to cholera outbreaks (Patrick et al., 2013). The latter is outside the scope of this review.

3.3. Chlorine stability

Another issue that arises with chlorination is the quality of the disinfectant used (e.g. sodium hypochlorite solution, tablets, etc.). Lantagne et al. (2011) found that the stability of hypochlorite solutions from different production techniques (and different target concentrations and pH stabilization) were generally stable for up to 19 months unless exposed to direct sunlight, which reduces the concentration significantly. During normal use in households in Kenya, the stability of hypochlorite in 48 sampled bottles showed that 77% of the samples were within 20% of the initial concentration of 1.2% hypochlorite. About 17% were 50% of the target concentration while 4% were only 20% of the targeted concentration. The hypochlorite was on average manufactured 433 days before the sampling was conducted. It is evident that if the product quality is poor either due to poor initial quality (i.e. inaccurate concentration) or as a result of instability and degradation over time, there is a risk of underdosing, especially if households do not use the product before the expiration date, which Lantagne et al. (2011) recommended as a minimum 1-year for 1.25% hypochlorite solution, given that the pH is above 11.9 and it is stored below 35 °C.

3.4. Disinfection by-products

During chlorination there is a risk of the formation of a wide range of disinfection by-products (DBPs), which can be harmful to human health and thereby give rise to concern. The formation occurs when chlorine reacts with organic matter present in the water and the type and amount of DBPs formed depends on factors such as the water quality, contact time, temperature, and pH (USEPA, 1999). However, research has shown that under field conditions, the DBP formation does not exceed the WHO guideline values with health significance in drinking water (e.g. bromodichloromethane – 60 μg/L, bromoform – 100 μg/L, dibromochloremethane – 100 μg/L, chloroform – 300 μg/L, dichloroacetate −50 μg/L, dichloroacetonitrile – 20 μg/L, bromate – 10 μg/L) (WHO, 2017), even when using highly turbid water (up to 888 NTU) (Lantagne et al., 2008, 2010). Even so, the fear of DBP formation and the potential negative health effects may still pose an obstacle for a high user compliance. In centralised water supply (WS) systems, water quality monitoring is common to avoid such issue, but the presence of DBP precursors is not likely to be regularly tested in self-supplied communities, which may pose an additional risk to this disinfection method and might be considered in future research.

DBPs are present at sub-μg·L^{-1} or low-to-mid-μg· L^{-1} levels in drinking water (Xiao et al., 2020). At household level DBPs can be controlled by limiting their production which can be challenged by reducing the natural organic matter (NOM) before disinfection or adopting safer disinfection methods (e.g., ferrate(VI)). When DBPs are produced, their removal must be in place, typically by activated carbon (AC) adsorption, after disinfection although the volatile DBPs can be eliminated using other household water treatments (Deng, 2021).

According to a recent investigation on the efficiency of several HWTS – AC and membrane filtration, boiling, UV lamps, cold storage or a combination of them – for the removal of DBPs in drinking water resulted on a significant removal of trihalomethanes (THMs) and haloacetic acids (HAAs) using all these HWTs except for storage. Their efficacy varied upon their purification mechanisms and depended on the chemical characteristic of the target DBPs (Xiao et al., 2020). It is also well recognised that pathogen removal should not be compromised in attempting to control DBPs, but also that more research is required on the trade-off between the chemical and microbiological risk during household treatment.

3.5. Evaluation of household chlorination

When dealing with chlorination, several indicators can be used to evaluate the outcome of an intervention. According to WHO and UNICEF (2012), these include the quality/presence of chlorine products in the household, FRC in the water, and improved water quality indicated by microbial indicators. FRC in the water can be an indicator of correct and consistent use as well as water safety and is therefore critical to monitor.

Some research has been done on the evaluation of drinking water treatment programs. The evaluation can be based on metrics such as the reported use, confirmed use, and effective use as illustrated in Fig. 1. Often the reported use is higher than the confirmed use and effective use and reported use is prone to being biased e.g. if users are affected by their participation in the intervention. Therefore, using self-reporting alone as an evaluation tool will typically overestimate the actual use of an HWT (Gallandat and Lantagne, 2018).

The lack of FRC in stored water does not necessarily mean that the HWT has not been performed by the user. It could also imply that the CD from raw water exceeded the applied dosage. This situation illustrates that different approaches are important to evaluate confirmed and effective use of the disinfectant. For instance, if there is no FRC, but a reduction in the pathogen threshold was found, this could indicate underdosing, an example of ineffective use. Incorrect use can be defined as either having too low or too high concentration of FRC. The latter will still provide safe drinking water, but it increases the risk of odour and taste issues.

4. Promotion of chlorination in rural settings in the Global South

In the 1990's, the Safe Water System (SWS) was developed by Centre for Disease Control and Prevention (CDC) and the Pan American Health Organisation, which combined chlorination with safe storage and behavioural change communication to improve the practices of safe storage, sanitation and hygiene (CDC, 2014b). These principles are being promoted worldwide by various non-governmental organisations (NGOs) such as Population Service International (PSI) and CARE and introduces chlorination both as liquid NaOCl (i.e. WaterGuard) and NaDCC tablets (i.e. Aquatabs).

Table 3 provides a summary of some intervention approaches and the key activities and outcomes related to these. The implementation strategies often combine collaboration with various stakeholders (e.g. governmental bodies, local leaders, and community health workers (CHWs)), training of local promoters, and education and information on topics such as water treatment, safe storage, hygiene, health, and causes of diarrhoea through personal interaction, community meetings and other activities in the communities as well as social marketing. These approaches built on creating acceptance as well as awareness of the products and health outcomes in communities, and in many cases result in an increased knowledge of the promoted products. Here, frequent household visits are often identified as a key factor in the uptake, where e.g. Wheeler and Agha (2013) observed that receiving household visits increased the likelihood of using and purchasing chlorine eight years after a WS and hygiene promotion campaign in Mozambique. However, these approaches do not always guarantee a high uptake of the treatment or consistent use as seen in Table 3.

The strategies vary in their financial approach, where some distribute a free supply of products during the study period, while others incorporate partly subsidized products or local companies and sales agent to ensure affordable products and distribution. The latter may be more sustainable in terms of long-term product supply in communities since it is not dependent on outside funding and ensures cost recovery. The drawback is that it may unintentionally exclude poorer parts of populations who are unable to afford the products even if they are available at a low cost. This trend was observed by Freeman et al. (2009), who found that the proportion of households who had detectable FRC in their stored water increased with increasing socioeconomic wealth and this was also associated with increasing awareness of chlorine products. The influence of cost was studied by Ritter et al. (2017) who showed higher purchase rates were associated with decreasing prices among rural Haitian households randomly assigned to five different prices of chlorine. Monthly household visits did not have a significant influence on the uptake at the two lowest prices nor at the highest price. At the low price, this indicates that some households do not need convincing to purchase, while others are unsusceptible to the promotional efforts. At the high price, household visits are not sufficient to overcome the price barrier. Similar price sensitivity was observed

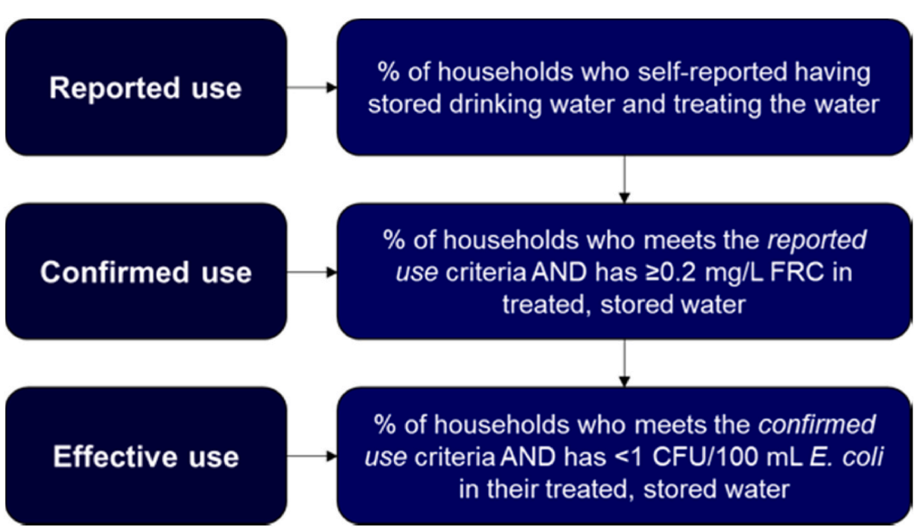

Fig. 1. Evaluation metrics for chlorination. Information from (Gallandat and Lantagne, 2018).

Table 3
Summary of strategies, activities, and outcomes for implementation of chlorination in rural communities. Sûr'Eau and Klorin are local brands of liquid NaOCl.

Country	Implementation strategy	Activities	Outcome
Rwanda (Chankova et al., 2012)	Implementation by PSI, the department for community-based health insurance (CBHI) scheme technical assistance at the Rwandan Ministry of Health and CBHI schemes in pilot districts. Training of 3,200 CHW, CBHI managers and committee members to promote and distribute Sûr'Eau to households in more than 1,100 villages. Training covered the technical aspects of household water treatment, management of Sûr'Eau stocks, and distribution and sales at the community level.	Regular small group out-reach sessions to provide education on safe water and sanitation, as well as to promote and sell Sûr'Eau at the community level. Promotion of safe water practices in general and Sûr'Eau in particular directly to households, including through interpersonal communication conducted during home visits and at community gatherings. Talks on safe water, hygiene, and sanitation, and promotion of Sûr'Eau to patients waiting to be seen at health centers.	After 18 months, the exposure to WASH (water sanitation and hygiene) messages was higher in the pilot districts compared to the control district. The knowledge of Sûr'Eau and its purpose increased by 10–35%-point among communities in pilot districts. In the pilot districts there was a decrease in the proportion of households that did not use any form of treatment of their drinking water, whereas this increased in the control district. At baseline, few households used any other treatment than boiling. After 18 months, 60% reported using HWTs every time they collected water, although this was not in total agreement with answers later in the questionnaires.
Madagascar (Ram et al., 2007)	Implementation by CARE Madagascar who trained community-based sales agent in four villages trained on causes and prevention of diarrhoea, proper use of the SWS, and techniques for changing health behaviours.	Sales agents conducted educational visits to neighbours to inform about the need for household water treatment and safe storage to prevent diarrhoea as well as to sell them Sûr'Eau and jerry cans with taps.	After 16 months, 99% of 242 surveyed households had heard of Sûr'Eau, primarily through CARE or the community-based sales agents. 95% of households reported using the product at least once, and of these 73% were currently using the product. 72% of current users were able to correctly state the dose, waiting time before drinking, and proper water storage procedure.
Malawi (Wood et al., 2012)	UNICEF, Ministry of Health and PSI promoted WaterGuard (liquid NaOCl) by distributing for free at antenatal clinics. Promotion of WaterGuard through media channels, i.e. radio announcements, signs, billboards, posters, and flyers. After the intervention, PSI continued its normal national distribution system and promotional activities for WaterGuard.	Distribution of free hygiene kits that included WaterGuard to 15,000 pregnant women attending health facilities. If enrolled in the program, the women were eligible to receive up to three free refills of WaterGuard at later visits. The women attending the health facility was educated by the health workers about health and hygiene, including water treatment and correct use of WaterGuard. Home visits by health surveillance assistants to reenforce educational messages.	Before the intervention, the awareness of WaterGuard was high. Three years after the intervention, the awareness of the need to treat household drinking water was high, where especially the influence of interpersonal communication with health workers and health surveillance assistants was reported as an important factor. After three years, participants varied between consistent year-round users, seasonal users, switching between different methods, and some no longer used WaterGuard.
Kenya (Makutsa et al., 2001)	Implementation of SWS by CARE in 12 rural villages by adopting community mobilisation and management structure of existing Water, Sanitation and Education for Health project. Support by Kenyan government officials, community management committees, and leaders of women's groups ensured. Agreement with a private company to produce 1% sodium hypochlorite (branded Klorin) and establishment of quality control system. Development of improved clay pots for safe storage. Subsidized and packaged with a free bottle of Klorin during the promotional period	Village health promoters held community meetings, schools, and village health training workshops to teach about SWS. Social marketing to encourage behavioural change, i.e. Klorin-themed posters, puppet shows, soccer tournaments, public product demonstrations, and Klorin quizzes with prizes. Village health promoters received T-shirts, water vessels, or Klorin bottles as incentives for meeting sales targets.	Before implementation, a survey showed that 90% used boiling as primary treatment but that most rarely treated their water even when acknowledging that contaminated drinking water causes diarrhoea. Six months after implementation, 33.5% of 173 surveyed households had detectable FRC and 18.5% were using the promoted clay pots.
Kenya (Freeman et al., 2009)	After receiving training on SWS by CARE Kenya, a local organisation, Safe Water and AIDS Project (SWAP) used a social entrepreneurship model of SWS dissemination. Unrelated to the SWAP activities, a number of self-help groups were selling PuR (combined flocculant-disinfectant), and	Training of SWAP group members on diarrhoea prevention and proper water treatment practices. SWAP group members were offered to purchase water treatment products (Klorin, PuR, and WaterGuard) at wholesale prices, sell them at retail prices to	After 2 years, 33% of 485 households in 6 rural villages and 2 peri-urban villages reported ever using Klorin, 9% using WaterGuard, and 10% using PuR. FRC attributed to Klorin was detected in 17.1% of stored water samples, while this was 2.5% for WaterGuard, and 0.8% for PuR.

(continued on next page)

Table 3 (*continued*)

Country	Implementation strategy	Activities	Outcome
	Klorin and promoted (but not selling) WaterGuard.	neighbours, and keep the difference as an incentive.	20% of the households reported repeat purchases of Klorin or WaterGuard, while 10% were still using their first supply. Only 5% reported having used more than 1 sachet of PuR and 1% had used more than 10 sachets.
India (Boisson et al., 2013)	Implemented by PSI by promotion and free distribution of NaDCC tablets. Training of interpersonal communicators.	Interpersonal communicators visited households fortnightly distributing free tablets, instructing on use, providing information on health and drinking water treatment, and engaging the households by using games and interactive pictures. Community-level activities including street plays, game shows, wall paintings, and distribution of information material	At baseline, 44% of households reported treating their drinking water by any form of treatment. Self-reported and confirmed use increased over the study period, with an overall 51% of household samples reported treated, and confirmed use was 32%. This varied between households, where 20% never had detectable FRC, and 76% had FRC on less than half of the visits.

among households in rural Kenya, where wealth was also a predictor of higher chlorine use, and health messages had little effect on households' decision to purchase chlorine (Blum et al., 2014).

5. Implementation of household-based chlorination

When chlorination is performed at the household level, NaDCC tablets or liquid NaOCl is often used. The commercially available chlorine-based products are typically of a high quality with only small deviations from the targeted concentration and are based on providing a fixed dosage of free chlorine. Common commercially available products such as WaterGuard comes in bottles, where e.g. the bottle cap is used as a measuring tool for a predesignated volume of water based on a target free chlorine concentration. The drawback with the fixed dosage-based products is that they require the household to have a certain size of container, which may not always be available. Therefore, there is a risk of incorrect dosing or discontinued use if the correct container size cannot be found (Kumwenda et al., 2014).

Field studies show that in some communities, local vendors buy concentrated NaOCl (10–15% free chlorine), which is diluted and resold in smaller plastic containers (Levy et al., 2014). This poses a risk of inaccurate dosing e.g. if the dilution is not performed correctly or the required dosage is not easily measured. Concentrations ranging from 0.9 to 15 mg/L in the treated drinking water were observed by Levy et al. (2014), when households used a locally diluted product in Ecuador. With the high concentrations of chlorine, the issues of increased risk of DBP formation and taste acceptability arise.

Chlorine solutions can also be produced locally i.e. by the electrolysis of brine using a simple electrolytical cell (Murray et al., 2020), dissolving calcium hypochlorite ($Ca(ClO)_2$), or injecting chlorine gas into a stream of deionized water (Lantagne et al., 2011). These products will have a lower quality in terms of the concentration of free chlorine (FC) and its stability compared to commercial products if the manufacturing and packaging are not of a high quality and thereby pose a risk of incorrect dosing if the target concentration is not met (Lantagne et al., 2011).

There can be a significant difference between the chlorination practices during drinking water treatment interventions for research purposes and the real-world conditions. According to Mclaughlin et al. (2009), the compliance rate is often higher in intervention studies compared to the actual situation. This can be caused by the oversight of investigators or the use of user surveys which may give biased results. In a rural community with no previous exposure to interventions or training, Mclaughlin et al. (2009) found that among nine households claiming to treat their water with chlorine, only two households reported always doing so during the 3-week study, while one household never chlorinated the water during the study. The remaining households reported chlorinating their water 14–77% of the time. There was no significant difference in the level of total chlorine between treated and untreated samples, but 50%, 58%, and 21% of the treated samples had detectable E. coli, enterococci, and phage respectively, compared to 86%, 82%, and 32% of untreated samples. Much higher self-reporting rates were found among 32 rural households in Zambia where about 42% of the households reported treated their water daily and 39% reported treating the water on every collection. However, this was partly contradicted by field observations i.e. unavailability of treated water upon visits (77%), reports of the available water being treated more than two days prior to the visit (50% of self-reported daily users) as well as inadequate FRC concentration of the drinking water present in the household (100%). In many cases, untreated water supplemented the treated water, and even among the self-reported users of chlorination, about half of the households reported drinking untreated water although they generally were aware of the associated risk to their health (Rosa et al., 2016).

One of the challenges with chlorination and the often-low observed effectiveness under field conditions is that, although confirmed and correct use can be validated, it does not factor in under which conditions chlorination is performed in the households. This is an area that has gained little attention and only a few studies have investigated how chlorination is practised, as summarized in Table 4. It is evident from these few studies, that applying the correct dose of chlorine can be problematic and across all three reports, no more than half of the respondents used the methods correctly. This proves, that even when users have an intent to treat, it may not always be enough to ensure safe drinking water. This is further complicated by varying source water quality, which would require the users to adjust the dosage. In the case of Malawi where 56% of respondents indicated either dosing correctly or overdosing, only 8% of water samples taken from storage containers in the households had an FRC concentration above 0.2 mg/L (Kumwenda et al., 2014). This discrepancy could be caused by non-treatment (over-reported use), high CD, or even recontamination during long storage time.

6. Efficiency, compliance, and sustainability of household chlorination

Chlorination of water at the point of use has been shown to reduce the risk of childhood diarrhoea (Boisson et al., 2013; Ercumen et al., 2015; Mengistie et al., 2013). Even so, in the past, field studies have shown that adopting and consistently using chlorination have been a challenge. If chlorination is practiced frequently, but the user does not consistently drink treated water (e.g. consumes untreated water outside the home) the compliance will still be low and thereby the health effects will also be low or absent (Murray et al., 2020; Patrick et al., 2013).

Looking at the short-term effect of interventions, case studies from Ethiopia have shown that two separate interventions with free supply of

Table 4
Practice and knowledge on correct use among rural households. HH: households. Sûr'Eau, Jif, and Clorox are local brands of liquid NaOCl.

Country	Project details	Product and correct use	Practice
Rwanda (Chankova et al., 2012)	2,402 HH studied over 18 months	Liquid Sûr'Eau: One bottle cap/20 L	About one third of respondents, who had used the method in past, could mention all 4 steps correctly; 1) Fill 1 bottle cap 2) Pour in 20 L jerry can 3) Close jerry can and shake well 4) Wait 30 min before drinking
Haiti (Patrick et al., 2013)	One-time survey of 433 HH 16 months after onset of cholera epidemic	- Aquatabs (available as 8.5,17, 33, and 67 mg): One 67 mg tablet/20 L - Jif or Clorox (5–15% active chlorine): 25 drops/ 20 L - PYAM tablets: two tablets (19 mg each)/20 L	Half of the Aquatabs users reported applying an acceptable dose, while 25% underdosed. 26% of Aquatabs users did not know how many tablets to dose and most thought that one tablet to 20 L water was correct, irrespective of tablet size. Liquid bleach users reported using the correct dose in 15.9% of the case. Almost 80% of the users were underdosing where the majority used five or less drops. All respondents using PYAM indicated underdosing
Malawi (Kumwenda et al., 2014)	One-time survey of 349 HH	WaterGuard: One bottle cap/10 L	330 HH reported to have used WaterGuard. Of these, 72% could explain how they treated the water, where 45% used the right dose, 44% underdosed and 11% overdosed. Of the WaterGuard users, 10% did not ensure mixing of the water after dosing.

WaterGuard had a high compliance during the 16-weeks study period. Here, on an overall average around 80% of households had FRC $\geq$0.2 mg/L during weekly or biweekly testing, which did not appear to decrease during the study period. Additionally, in both studies there was a significant improvement in the water quality and the proportion of water samples with detectable E. coli as well as the bacterial count (Mengistie et al., 2013; Solomon et al., 2020, 2021).

Similar results were reported by Rangel et al. (2003) in a study comparing a combined flocculation-disinfection product to regular diluted bleach and safe storage among rural households in Guatemala. Overall, water samples collected weekly during 4 weeks from households using bleach showed that 83% had FCR above 0.5 mg/L and 92% had less than 1 CFU/100 mL of *E. coli*, which demonstrates a high initial compliance. In contrast to this, a study from India showed a declining compliance to chlorine delivered free of charge, where the proportion of samples with <1 thermotolerant coliforms (TTC)/100 mL was about 32% after 1 week and declined to 7% after 4 months. This was attributed to inadequate chlorine dosing, low compliance due to a high resistance towards chlorination as well as in-home recontamination (Firth et al., 2010).

While some authors argue that the uptake of chlorine products is likely to be lower in the absence of free provision and intensive promotion (Ercumen et al., 2015), Garrett et al. (2008) found that in a combined water, sanitation, and education for health (WASEH) intervention in Kenya, where a low-cost chlorine product was promoted, FRC >0.1 mg/l was measured in 43% of stored water samples during weekly visits over 8 weeks. Although this intervention was limited in time, it indicates that free product distribution in not always the most essential motivator, but user acceptability may play a far more significant role when looking at the short-term compliance. Furthermore, comparison of short-term interventions can be complicated by the time of the year that they are conducted, i.e. during the rainy season, where the perceived risk of contamination is higher and therefore the incentive to treat water is higher (Wood et al., 2012).

For chlorination to be an effective and sustainable solution for securing safe drinking water, it is necessary to also look at the long-term compliance. Table 5 summarises the experiences from studies that lasted 10 months or longer. The results from these evaluations are varying significantly in their level of compliance, where the cases from India and Bangladesh are somewhat similar in their approach (frequency of visits, free distribution) but the compliance and disinfection efficiency was about twice as high in the study from Bangladesh. This suggests, that although frequent home visits and educational activities are important driving factors for a high and consistent uptake, other factors influence this as well and will vary across geographical regions. In the case of the Indian study, the intervention did not provide appropriately sized storage containers but reported that the typical container size in the households was 13 L, which is considerably smaller than the 20 L prescribed size for a 67 mg NaDCC tablet used in the study. Overdosing and consequently rejection of the treatment could be a contributing factor to the lower compliance.

Although chlorine on its own has been shown to reduce childhood diarrhoea (Crump et al., 2005), interventions that combine water treatment with other WASH (water, sanitation and hygiene) components have shown positive influence on the reduction of childhood diarrhoea. It is therefore interesting to look at these types of interventions to see if an increased focus on hygiene and sanitation has an impact on the compliance of water treatment. For comparison, Table 6 therefore summarises three studies where household chlorination has been introduced in communities in combination with other WASH components. In all studies, the compliance increased over time, but in the two studies that compared several treatment arms, the chlorine alone treatment arm interestingly had the highest compliance. Opryszko et al. (2010) argued that when multiple health messages and behaviours are promoted in combination, there is a risk that the messages will be diluted, and the inconvenient and time-consuming behaviours will be downgraded. However, the combined effects (even at lower treatment compliance) in terms of health improvements can still be greater compared to standalone chlorination.

7. Barriers and enablers for adequate implementation

The adequate implementation of chlorination in a household faces several barriers and enablers. These have different origins and can be divided into *user*, *chlorine product*, and *correct practice and storage* which are summarized in Table 7, Table 8, and Table 9 respectively.

Barriers that are directly related to the *user* include the user demand for HWTs. As seen in many field trials, there is often a lack of motivation to use the HWTs or a lack of understanding of the benefits, which leads to low user compliance and/or non-use. HWT is a preventative practice where the benefit, e.g. the aversion of diarrhoea incidences, is not obvious to the user immediately. Geremew et al. (2019) found that households in Ethiopia were more likely to use a chlorine product over time when they believed that it made their water safer to drink. This demands for better implementation strategies, including appropriate

Table 5
Examples of long-term effect of interventions or emergency responses focused on water treatment only. Sample size refers to the intervention participants (not including controls) at end line. HH: households. SS: safe storage. Gadyen Dlo is a local brand of liquid NaOCl.

Location	Sample size	Duration and frequency of visits/testing	Treatment	Effect on microbial quality	Compliance
Haiti (Lantagne and Clasen, 2013)	143 HH	10 months 1 follow up visit 10 months after an emergency response.	Free Aquatabs/Gadyen Dlo	46% of HH had *E. coli* <1 CFU/100 mL 41% of HH had *E. coli* <10 CFU/100 mL	81% of HH reported as current users. 90% of the treated samples had FCR above 0.2 mg/L
India (Boisson et al., 2013)	751 HH	12 months Biweekly educational visits Monthly testing visits	Free 67 mg NaDCC/bucket (about 13 L)	Overall mean 50 CFU/100 ml TTC (control 122 CFU/100 mL TTC). Reported use mean 24 CFU/100 mL TTC (control 138 CFU/100 mL). 37% of reported-use samples free of TTC (20% in control).	Confirmed use increased from 14% at baseline to 47% at end line. 30% of samples with detectable FRC exceeded the recommended 2.0 mg/L, where 11% was equal to or exceeding 5.0 mg/L.
Bangladesh (Ercumen et al., 2015)	537 HH	12 months Monthly promotion visits Monthly testing visits	Free 33 mg NaDCC/10 L + SS	74% of samples free from *E. coli* (11% in control). 9% of samples with *E. coli* >10 CFU/100 (61% in control). 2% of samples with *E. coli* >100 CFU/100 (21% in control).	91% of spot checks had stored water in the provided container. HH who had water stored during visits with FRC ≥0.2 mg/L varied between 76% and 90% during the study period.
Kenya (Parker et al., 2006)	51 health clinic clients	12 months Home visits after 2 weeks and 1 year	WaterGuard		71% of stored water samples had detectable FRC after 1 year
Guatemala (Rangel et al., 2003)	83 HH 87 HH w. SS	12 months Weekly visits 3 follow-up testing visits and monthly unannounced testing visits	Free chlorine bottles±SS	61% (+SS) and 51% (- SS) of samples on unannounced visits had <1 CFU/100 mL *E. coli*	On monthly unannounced visits, 44% (+SS) and 36% (- SS) of HH had FRC >0.1 mg/L
Haiti (Murray et al., 2020)	59 HH	13 months 4 follow-up testing visits	Free handheld electro chlorinator with target concentration of 2.5 mg/L chlorine in treated water	82% of samples free from *E. coli* 11% of samples with *E. coli* >10 CFU/100	Confirmed use ranged from 39% at two weeks to 13% at 13 months. 2% had confirmed use on every visit 77–91% reported drinking untreated water
Haiti (Harshfield et al., 2012)	201 HH	Up to 8 years after implementation 1 follow-up testing visit	Gadyen Dlo (NaOCl) + safe storage		75% of HH self-reported current use (10% of control), where 34% reported daily use (11% of controls) 56% confirmed use in the range 0.2–2.0 mg/L (10% of control).

HH: households, SS: safe sanitation, +SS: with safe sanitation, –SS: without safe sanitation.

behavioural intervention, including education and training in health and hygiene, to underline the benefits of treating the water both in terms of health outcome but also economic benefits e.g. higher school attendance, reduced number of missed workdays, and reduced expenditures on healthcare. However, even regular educational visits to households does not guarantee a high level of compliance (Boisson et al., 2013). Other user-related barriers include the user acceptability and preference. In terms of chlorination, one of the most frequently reported objections to chlorine is smell and taste. This is especially a problem when the users are not used to chlorine e.g. in the public WS. The user preference of technologies also plays an important part since some users will prefer methods that do not require regular purchases or offer a more convenient usage (Ercumen et al., 2015). Furthermore, in rural communities there may be cultural factors that cause a low adherence to the methods e.g. due to misconception/false rumours of chlorine toxicity or if water is associated with healing powers or being of a religious value to the people.

Barriers related to the *chlorine product* include the affordability and supply chain. Although chlorine products are generally cheap, they need to be replenished continuously and add an extra cost for households. Therefore, their willingness to pay after an intervention is implemented is very important, which is related to their awareness of the benefits of treating the water and the cost averted as a result thereof. However, in cases where chlorine is distributed free of charge, a low compliance can sometimes be observed, indicating that other factors contribute as well. Furthermore, it is seen that discontinued use after an intervention can be related to the lack of a supply chain in the communities, which can provide the chlorination products continuously. Prior to an intervention, it should therefore be investigated if the supply chain is sustainable. Although product quality is not reported as a concern by users, it is an important issue as discussed earlier. Therefore, product quality should be ensured through quality controls, especially when locally made products or diluted commercial products are used, where a poor quality may lead to ineffective treatment and false sense of security.

The lack of knowledge on *correct use and practices* is a significant barrier to the successful implementation of chlorination, where variations in available product concentrations and appropriate storage container size can lead to incorrect dosing. Underdosing will give a false sense of security, while overdosing may lead to rejection of the method due to taste issues. Although chlorination is seen as a simple method, identifying the correct practice can be a challenge for users as already discussed. Users who feel comfortable using the method have also been found to be more likely to continue to do so (Inungu et al., 2016). The successful implementation and adoption of HWT requires a significant behaviour change since consistent use requires an active choice to treat the water every time it Is collected and not just when the perceived risk of contamination is high. The behaviour change also means being aware of the risk associated with consuming untreated water and to stop that behaviour.

The common trait of many of these identified barriers is their common mitigation measures. Although most interventions are accompanied by information, education, and/or training to generate awareness of the importance of treating water, it has been shown that users prefer clearer messaging about the health benefits of safe water especially from

Table 6
Long-term effect of interventions or emergency responses combining water with other intervention types. Sample size refers to the intervention participants (not including controls) at end line. HH: households SS: safe storage. Clorin is a local brand of liquid NaOCl.

Location and intervention	Sample size	Duration and frequency of visits/ testing	Treatment	Compliance
Afghanistan (Opryszko et al., 2010) **a) Water b) Water, hygiene education, and improved water source**	288 HH Water 255 HH Combined	16 months Biweekly visits	FC (0.05% NaOCl) + SS	Self-reported use increased from overall 7%–72% in Water group and to 78% in Combined group. In both groups, the majority used Clorin as treatment (98% of Water group and 76% of Combined group).
Bangladesh (Parvez et al., 2018) **a) Water b) WASH c) WASH and nutrition**	698 HH Water 703 HH WASH 686 HH WASH + N	20 months Monthly visits	FC tablets + SS	Over 20 months, 84% of households in the Water group self-reported treating their water, while this was 78% for the WASH group, and 77% for the WASH + N group. Confirmed use was 76% for households in the Water group, 68% for WASH and 67 for WASH + N group.
Malawi (Loharikar et al., 2013) **Water and education (WASH) facilitated by antenatal care service**	232 pregnant women 386 relatives/ friends	3 years 1 follow-up survey after 1 year and after 3 years	Free WaterGuard (up to four free bottles) + FC stock during rainy season	Self-reported use increased from 44 to 69% of WaterGuard and 13–47% for chlorine stock solution among participants. Confirmed used increased from 9% to 54% among participants and 9%–43% among friends/ relatives

highly trusted sources of health advice such as nurses and health workers (Makutsa et al., 2001; Parker et al., 2006) rather than mass media (Freeman et al., 2009). Ongoing, positive interactions with health advisors (Wood et al., 2012) as well as high frequency of receiving instructions and/or home visits (Loharikar et al., 2013; Parker et al., 2006) have been observed to be some of the main driving factors for a high and sustainable compliance. This was also confirmed in an exploratory study about the challenges of tablet chlorine programs in emergencies. Interviews with emergency WASH professionals revealed that frequent distribution accompanied by education messages was key to a successful implementation. However, it was also found that if the individuals

Table 7
User dependent barriers and enablers to adequate implementation of chlorination based on field experience.

	Barriers	Enablers
Motivation	Lack of understanding of the importance of consistent use of treated water. (Patrick et al., 2013) Inability to acknowledge the link between health benefits and technology use. (Freeman et al., 2009; Roma et al., 2014) Perception of drinking water sources to be safe without treatment, i.e. due to natural treatment, protection, and clarity. (Freeman et al., 2009; Kumwenda et al., 2014; Lantagne and Clasen, 2013; Loharikar et al., 2013; Patrick et al., 2013).	Perceptions of health benefits generated by chlorine disinfection. (Roma et al., 2014). Perceived need for water treatment to prevent diarrhoea (Makutsa et al., 2001; Parker et al., 2006; Rosa et al., 2016; Wood et al., 2012). Desire to prevent sickness and protect their families. (Wood et al., 2012).
Acceptability	Dislike smell and/or taste even at low concentrations (Boisson et al., 2013; Freeman et al., 2009; Kumwenda et al., 2014; Mitro et al., 2019; Parker et al., 2006; Roma et al., 2014; Wood et al., 2012) Preference of other methods. (Kumwenda et al., 2014) Distorted perceptions of health benefits or problems caused by chlorine (i.e. infertility). (Makutsa et al., 2001; Mitro et al., 2019; Roma et al., 2014) Do not fully trust the method (Rosa et al., 2016)	Pre-existing experience with chlorine can reduce the sensitivity to taste and smell. (Mitro et al., 2019) Getting accustomed to the smell and taste, i.e. associating it with safety and good health. (Wood et al., 2012) Frequent distribution accompanied by education messages (Mitro et al., 2019) Interest in chemical disinfection (Makutsa et al., 2001)
Culture	Cultural perceptions of cause for contamination/disease. (Kumwenda et al., 2014) Cultural perceptions of chlorine products, i.e. causing diseases. (Roma et al., 2014) Water may be considered to have healing powers. (Roma et al., 2014) Low uptake of products, i.e. safe storage containers due to resistance towards non-traditional materials. (Ram et al., 2007)	Culturally appropriate educational methods (Parker et al., 2006).

conducting the training/education lack experience with the technical and/or behavioural aspects of water treatment, it will pose a barrier. It was also noted that the educational messages should be accompanied by implementors drinking water treated in the same way as they promote it. In some cases, it can also be relevant to include inputs from social scientists, who can assess the cultural and educational needs in a community (Mitro et al., 2019).

Although chlorination has been shown to be an effective approach to the disinfection of potable water, a significant limitation is that it is only effective under very specific conditions, and incorrect practices or discontinued use often lead to low efficiencies in the field. In the past, research has focused on either the quality of the water (i.e. in terms of presence of pathogens) and/or the presence of FRC concentration without considering the actual practices of chlorination. It is therefore uncertain if the reported failures are caused by user-dependent factors such as insufficient contact time and incorrect dosing, or if external factors such as high CD, poor quality of the product, or water/container recontamination are causing this.

While chlorination as an HWT only achieves a 1-star classification by the WHO, it can still be a highly effective solution to the disinfection of water containing bacterial or viral pathogens as it is easy to use and has a

Table 8
Chlorine product dependent barriers and enablers to adequate implementation of chlorination based on field experience.

	Barriers	Enablers
Cost	Lack of affordability (Freeman et al., 2009; Kumwenda et al., 2014; Loharikar et al., 2013; Opryszko et al., 2010; Parker et al., 2006; Patrick et al., 2013; Ram et al., 2007; Rosa et al., 2016). Use of less chlorine than directed on the bottle in order to make a bottle last longer (Mclaughlin et al., 2009). History of receiving free goods from NGOs, etc. (Makutsa et al., 2001)	Users see an economic value if it will save them money spent on water from vendors or fuel/wood for boiling. (Roma et al., 2014). Willingness to pay (Makutsa et al., 2001; Wood et al., 2012). Affordability, i.e. in comparison to other methods used by consumer (Makutsa et al., 2001; Parker et al., 2006). If perceived benefits outweigh the product's cost as long as users have the money to pay for it. (Wood et al., 2012). Extended free trial allows trying unfamiliar products without financial risk and should give sufficient time to experience health benefits. (Wood et al., 2012). Free access to products (Loharikar et al., 2013).
Availability of product	Unaware of the products or where to buy them. (Freeman et al., 2009; Loharikar et al., 2013). Lack of availability of products (Patrick et al., 2013; Rosa et al., 2016). Not aware of the presence of products in community (Freeman et al., 2009; Kumwenda et al., 2014). Product distribution challenged by poor road conditions and large distances between communities (Makutsa et al., 2001)	Knowledge of where to buy products. (Inungu et al., 2016; Loharikar et al., 2013). Ease in accessing the products (Makutsa et al., 2001; Wood et al., 2012).

Table 9
Current practice and storage dependent barriers and enablers to adequate implementation of chlorination based on field experience.

	Barriers	Enablers
Knowledge	Lack of understanding of correct use of products. (Mitro et al., 2019; Patrick et al., 2013). Confusion caused by use of multiple product types and products with different dosages (Mitro et al., 2019; Patrick et al., 2013). Extended storage time can contribute to the loss of FRC. (Patrick et al., 2013). One-time distribution without proper instruction. (Mitro et al., 2019)	Availability of products with different dosages may ensure that appropriate dosage is available for different container sizes (Mitro et al., 2019). Ease of using (Makutsa et al., 2001; Wood et al., 2012). Users feeling comfortable treating the water with product. (Inungu et al., 2016).
Behaviour	Lack of time to treat water (Murray et al., 2020; Roma et al., 2014). Forgetting to treat the water (Murray et al., 2020). Consumption of untreated water when outside of the home. (Murray et al., 2020; Patrick et al., 2013). Seasonal variation in compliance due to e.g. dry season when perceived risk of contamination is perceived as low (Wood et al., 2012).	Support of their family and the broader community can give incentive for behaviour change (Wood et al., 2012). Higher compliance when perceived risk of contamination is high, i.e. during outbreaks Patrick et al. (2013)

residual effect. This is especially true in emergency situations e.g. due to outbreaks of cholera, where *Vibrio cholerae* is effectively inactivated by chlorine. Similarly, chlorination can be an ineffective HWT, e.g. against *Cryptosporidium*. Unfortunately, few studies deal with this topic prior to implementing an HWT, which could also influence the effectiveness on health outcomes. Pre-intervention screening of the predominant pathogens in an area could prove to be an important decision-making tool when deciding on which HWT to implement.

8. Safe water and chlorination in Mexico, Colombia, and Brazil

In Latin America, there has been progress since 2000 in the coverage of drinking water service levels, as illustrated for Brazil, Colombia, and Mexico in Fig. 2. These countries are part of the GCRF-UKRI funded SAFEWATER research program focused on providing safe drinking water to rural communities in Brazil, Colombia, and Mexico (GCRF-UKRI, 2020). The service level, *safely managed water sources* is seen as a basic human right. These sources are improved sources, which have the potential to provide safe water due to their design/construction and additionally, the water should be available on premises and when needed. The other service levels include *basic* (less than 30 min round trip collection), *limited* (improved, but more than 30 min round trip collection), as well as *unimproved* (not protected against contamination) and raw *surface water* (WHO and UNICEF, 2017).

It is evident from Fig. 2, that rural households still lag behind their urban counterparts, where only rural households in Colombia are partly covered with safely managed drinking water sources. Rural areas pose a challenge since they are difficult to reach with on-premises safe drinking water. In Mexico, although more than 99% of the population had achieved at least basic drinking water services in 2017, both the rural and urban population are challenged by improved sources not being free from contamination (UNICEF and WHO, 2020). Although Fig. 2 does not show very significant differences between rural and urban areas of Mexico in the drinking water service level, there are many specific considerations that are not fully evidenced in the current data, and which would affect the actual conditions of the service: for example the type of basic service, the volume of water served, the continuity, etc.

Disaggregated data from Mexico shows that there was a difference in the coverage when differentiating between the poor and rich, where e.g. 88% of the poorest rural population had access to the basic service level compared to 99% of the richest rural population. This difference was even more pronounced in Colombia, where 58% and 93% of the poorest and richest respectively had access to at least basic service level in rural areas. No disaggregated data is available for Brazil (WHO and UNICEF, 2020).

In the following, the real scenario observed in rural communities of the three Latin American countries are described, where the focus is on household chlorination as an interim solution to provide safe drinking water in rural areas. There can be challenges to its implementation and compliance that differ on a regional scale and even chlorination of public water supplies can be a challenge in these areas as well as in the urban areas.

8.1. Chlorination in Mexico

In Mexico, chlorination is predominant in public water supplies, where the target FRC varies between 0.2 and 1.5 mg/L aligned with the Mexican drinking water regulations (Haro et al., 2012). However, it is insufficiently and intermittently applied, as confirmed by monthly evaluations of disinfection efficiency performed by the Federal Commission for Protection against Health Risks (COFEPRIS). The evaluations are carried out on sample parts of the public WS throughout the country

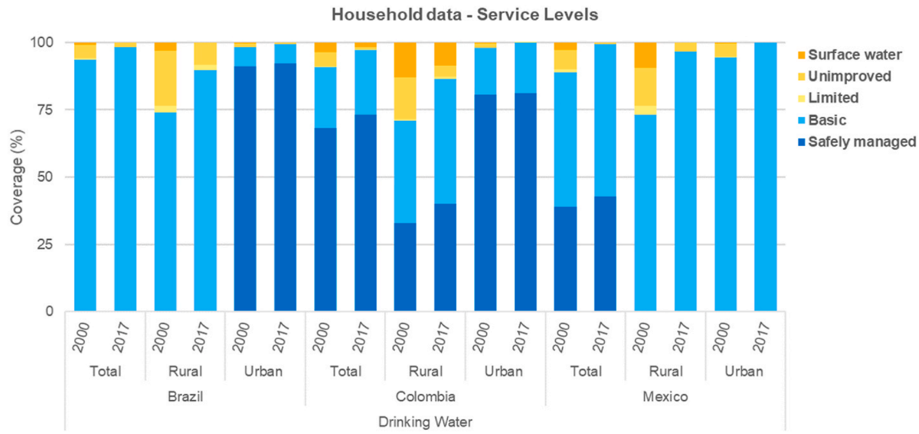

Fig. 2. Coverage (%) of drinking water resources at households in rural and urban areas of Brazil, Colombia and Mexico in years 2000 and 2017. Data from WHO and UNICEF (2017).

and showed that in 2016, only 47% of the sampled systems were efficient (i.e. more than 90% of the samples in a year meet the Mexican standard for FCR). In 22% of the systems, all the samples analysed were outside the Mexican standard in at least one of the monthly evaluations. In 4% of them, none of the samples from any evaluation met the standard (COFEPRIS, 2016). This poses a risk of deterioration of the water quality since most Mexican households store water either in tanks on rooftops or underground to ensure access to water, due to the generalized problem of intermittent WS. Only 45% of the country's population has a daily and continuous service of piped water. The rest of the population is subject to intermittent supply with variable frequencies (part of the day, every third day, once or twice a week) (INEGI, 2000).

Concerns regarding insufficient chlorination of public water supplies in Mexico are supported by several studies (Félix-Fuentes et al., 2007; Galdos-Balzategui et al., 2017; Rubino et al., 2019). In San Cristobal de Las Casas, Galdos-Balzategui et al. (2017) found that 32% of water samples from the public supply system had detectable *E. coli* in an annual monitoring of the bacteriological water quality, thereby confirming the irregularity in the disinfection process. In Guadalajara, Rubino et al. (2019) found that only 35% of 51 households had FRC meeting the required concentration and about 10% exceeded the FRC threshold. The FRC values fluctuated even from day to day in the same locations. Lower FRC concentrations were observed in water stored in households. Coliforms were observed in half of the tanks but in the study, only 8% of the households reported using the water for drinking and generally had a low confidence in the quality of the supplied water.

It should be noted that there are no national statistics for water quality monitoring of rural WS systems. COFEPRIS only provides surveillance to formal denomination systems, that have the necessary components to perform chlorination, which most rural systems do not have. In Mexico there are 49,440 locations with between 100 and 2,500 inhabitants, which are not part of the COFEPRIS evaluation system (CONAGUA, 2018). A study conducted by the Inter-American Development Bank and the NGO Cántaro Azul in 300 rural communities showed that only around 17% of piped WS systems met the FRC standards and more than 41% tested positive for the presence of *E. coli* (unpublished data). Navarro et al. (2007) found that in four studied rural communities, water samples from households at the water intake point and after passing through individual storage tanks only met the required FRC 59% and 49% of the time, respectively. Félix-Fuentes et al. (2007), studied the FRC level in three rural communities in the state of Sonora, and found that none of the water samples had detectable FRC in two of the communities, while 92% of the water samples from the third community were within norm.

A large part of Mexican rural communities, especially the most marginalized areas such as indigenous areas, are supplied with drinking water without any treatment. In these locations, not even chlorine is added to the community storage tank, since people reject chlorination (Soares, 2007). The general poor water quality of public water supplies means that many households must treat their own water to ensure potability (Vásquez et al., 2009). However, many choose to purchase bottled water instead, even in rural communities reaching up to half of the rural households (INEGI, 2018). Despite the need for water treatment, the research within HWT in rural Mexico is limited. In a study of a municipality in an indigenous region, boiling was the most reported treatment method among women respondents. The women reported the understanding of the relationship between water and health but, in fact, this could be associated with conditioning of a grant payment of the Prospera Government Program to women who meet the guidelines for hygiene behaviour, including boiling water for domestic use (Soares, 2007).

Today, to guarantee access to safe drinking water in Mexico, multiple strategies are needed. Governments need to develop public policies to improve the quality of the service of existing piped water systems and guarantee FRC values. Since the situation across the country in not likely to change in the short term, HWT is an important solution to increase access to safe water in rural and peri-urban communities. Although chlorination appears to be a common and effective treatment method in public WS, there is no relevant published scientific data on chlorine implementation in Mexican rural communities.

8.2. Chlorination in Colombia

The incorrect provision of drinking water and sanitation services in the rural sector and small municipalities is a common problem in Colombia (Quiroga et al., 2015). Although most Colombian rural communities have access to water, which is brought to homes through pipes, hoses, containers, or wells, only 42% of the rural population consumes safe water according to governmental sources (Colombia, 2018). There is only scarce information on the water quality in rural areas, which prevents knowing the real situation and consequently complicates adopting intervention strategies (Guzmán et al., 2015).

In urban areas in Colombia, chlorination is the most widely used disinfection method (RAS, 2010), but its application is not necessarily effective. In a study of chlorination in a pilot section of the drinking water distribution system in Cali, supplying approximately 30,000 inhabitants, it was found that the FRC was above the recommended 0.3 mg/L 80% of the time in the nine sampling points and never exceeded 1.0 mg/L. Lower concentrations of residual chlorine were observed when the residence time exceeded 24 h and at low water velocities in the pipes (Sánchez et al., 2010). It should be noted that the study did not mention the microbiological quality and thereby the potability of the water.

Regarding rural areas, although sodium and calcium hypochlorite are available at health posts (RAS, 2010), the use of chlorination is challenged by low initial motivation and commitment of communities to maintain disinfection on a continuous and reliable basis, the lack of understanding of the importance of disinfection, and the scarce financial resources necessary for the proper operation and maintenance of the disinfection system (Quiroga et al., 2015).

At community level, Ávila de Navia et al. (2016) studied the water quality in the rural community El Charo, which is supplied by an aqueduct and the water treatment consists of a decanter tank, a multi-layer gravity filtration unit and disinfection with chlorine. The aqueduct of the rural community supplies water to 28 houses and a school. The water quality was analysed twice at several points, including the raw water and three delivery points (taps), namely one school, and a house with and without a storage tank. Coliforms and *Enterococcus* were present in the untreated water at concentrations up to 96 and 54 CFU/100 mL respectively, which was generally reduced during the treatment process. At the delivery points, only the household with a tank contained coliforms, but on the second sampling event, all delivery points had *Enterococcus*. All samples were free from *E. coli* (Ávila de Navia et al., 2016). The results indicate the need for improved process control to ensure that the water is completely disinfected as well as the importance of cleaning storage containers at the household level to prevent recontamination.

There is no published literature on the use of chlorination at household level in rural Colombia, but according to RAS (2010), laundry bleach (5.25% sodium hypochlorite) is used in some rural areas. Through interviews in the rural communities of Curití and El Carmelo in Antioquia, Colombia in the SAFEWATER project (GCRF-UKRI, 2020), it was found that although the communities were aware of the risks associated with untreated water and the willingness to implement treatments to improve the water quality, there was a resistance towards chlorination due to the alteration of taste of the water (unpublished data).

8.3. Chlorination in Brazil

In Brazil, chlorination is much more widespread in rural and isolated communities. Nationally, the most recommended chlorination practice for HWT is the use of 2.5% chlorine solution. The national Ministry of Health distribute, free of charge, bottles containing a 2.5% sodium hypochlorite solution and it is suggested to use 2 droplets (approximately 0.1 mL) for 1 L of water and a contact time of 30 min (Brazilian Ministry of Health, 2011) (Fig. 3a). Commercial and concentrated bleach, although it is not recommended, is also used for water treatment in some households. However, these methods depend on the user's proper dosage and storage. NaDCC tablets are also used for water disinfection in Brazil, where the recommended dosage is one tablet (2g) to treat 1000 L of water within 15 min.

The implementation of these chlorination methods in rural communities in Brazil is not consistent. In the Northern region, De Souza et al. (2016) showed that the chlorine treatment was performed by 0% and 20% of the households in a study of two communities. In another study of 97 households across 10 rural communities in the semi-arid region, 36% used chlorine tablets for drinking water disinfection, but chlorine was only detected in one sample (Peres et al., 2020). In the Northeast region, 24% of 66 studied households used chlorine prior to consumption (Xavier et al., 2011). The low adherence to this treatment was mostly reported due to: i) taste and odour caused by chlorine; ii) the lack of convenience to treat water every day; and iii) the belief that the water had good quality.

To increase the compliance and adequate dosage, different types of diffusion chlorinators have been used in Brazil. The Brazilian Agricultural Research Corporation developed a low-cost chlorinator (Fig. 3b), which can be installed by the user with PVC tubes between the water intake inlet and the home reservoir (up to 1000 L) (Rodrigues, 2013). The Brazilian National Health Foundation developed a similar chlorinator suitable for reservoirs from 5000 L to 20000 L (Funasa, 2014). Both systems use granular calcium hypochlorite with 60–65% of active chlorine and consist of a point-of entry intervention, which reduces dependence on dosing at the point of use.

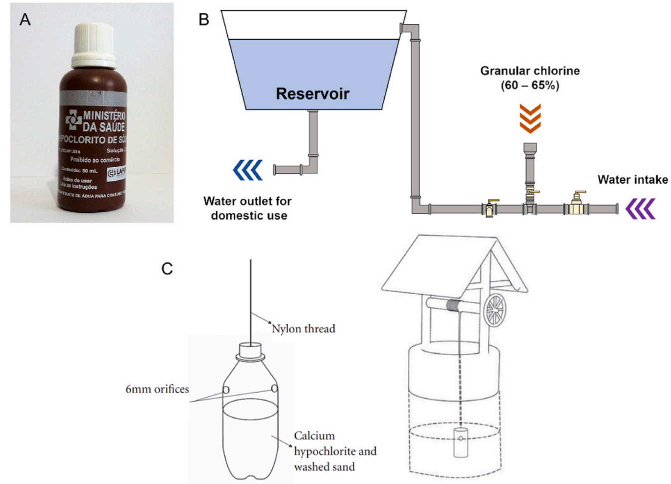

Fig. 3. A) Flask of 50 mL of 2.5% sodium hypochlorite distributed by the Brazilian Ministry of Health to population that are not supplied with treated water. B) Schematic of diffusion chlorinator developed by The Brazilian Agricultural Research Corporation, adapted from (Embrapa, 2015). C) Diffusion chlorinator made of plastic bottle fulfilled with sand and calcium hypochlorite, from (Ferreira et al., 2016).

Ribeiro et al. (2018) evaluated the water quality from 20 rural schools in the Brazil's Northern region, prior and after the use of diffusion chlorinators. Prior to implementation, the bacteriological analysis from the water supplied showed that 100% and 70% were positive for TC and *E. coli*, respectively. After applying the chlorinator, only 25% of the schools presented TC and all of them were free from *E. coli.*

An older and simplified diffusion chlorinator, but still common in some Brazilian household wells, is made of a plastic bottle filled with sand and calcium hypochlorite (Fig. 3c). The chlorine can diffuse homogeneously into water by the two small holes at the top of the bottle, which is immersed in the well. It is reported that this system can ensure safe water for up to 30 days, depending on organic matter content in water.

This type of chlorinator was implemented in 11 wells in a rural community which were contaminated by TC (8 to >1,600 MPN/100 mL) and *E. coli* (4–50 MPN/100 mL). Ten days after the chlorinator implementation, no samples presented bacterial contamination. After 20 and 30 days, only one well was presenting TC counting, however the chlorine was not detectable. The users reported that in the first 3 days after implementation the taste and odour of chlorine was stronger, but after 10 days there was no more complaining. It is important to highlight that despite the efficiency observed in this study, the free chlorine concentration was always below the recommend by the Brazilian legislation (0.5 mg/L) (Guerra, 2006).

Another study in Brazil's Northern region used the same diffusion chlorinators in 20 wells contaminated with TC and *E. coli*. After 2 days of implementation only one sample was still contaminated. However, after 30 days 75% of the wells were presenting TC and 35% were presenting *E. coli* (Ferreira et al., 2016).

9. Concluding remarks

Chlorination has many advantages such as being very cost-effective, simple to use, and can be made widely available. This suggests that it would be easy to achieve good results when implementing in households in rural communities, where the use is promoted by NGOs, local organisations, and governments.

In this review, we identified the main challenges of chlorination at household level, being the most relevant HWT the high user-dependence of this method to achieve high efficiency in disinfecting drinking water, the necessity of some technological approaches to apply the correct chlorination dose, the high risk of producing undesirable taste, smell and DBPs when the source of water has a certain organic matter content, and the chlorine dose is not accurately estimated by experts.

Despite that chlorine is the most effective, cheapest, easiest, most accessible and affordable household water treatment intervention, this paper also recognised the low compliance of chlorination as a big issue in rural settings and in the Global South in general. This is often attributed to the lack of motivation of the end-users, which points out at the need for research on user-behaviour changes in relation to water treatment and water quality awareness as well as the risks associated with consuming untreated water.

Social factors are often neglected in research done by scientists and engineers. For example, objection to the taste and smell of chlorine may even cause households to opt out drinking the disinfected water, as illustrated by the status of chlorination in Mexico. Even in public water supplies, the use of chlorine is challenged by insufficient dosing, as seen in Mexico, Colombia, and Brazil. Very few rigorous studies combine the social, scientific and engineering aspects to understand the challenges of real domestic scenarios, to investigate the limitations of existing technologies and to propose alternative approaches to face these issues. This illustrates the need to carry our more research in this area to change users' behaviour in the long term, improve compliance rates and reduce the high rates of users drop from chlorination programmes.

When the compliance concern is overcome, practical matters rise, as insufficient dosing found in Mexico, Colombia, and Brazil. This highlights the challenges associated with the technology and the need for capacity building when introducing an intervention. Here, we recommend that any public health solutions are accompanied by investigations aiming to avert taste and disinfection by-product issues at household, provide water quality assessment and pathogen screening, determine the potential need for multi-barrier approaches, as well as the design of user-friendly devices (e.g., inline chlorinators).

Microbiological contamination of water is a significant risk for rural communities in the Global South and is associated with deficiencies in water treatment and distribution. Intermittent supply, leaks, poor water quality and poor maintenance are common issues in rural areas. Barriers for an appropriate implementation of chlorination are responsible for low rates of success. The absence of risk assessment and the limitation for characterization, sampling and detection of biological contamination is a critical barrier. There is a lack of knowledge on the correct implementation of chlorination, which fails due to inadequate dosage, incorrect practice, and discontinued use causing low efficiencies in the households. Monitoring and evaluation of water sources in rural communities is a main barrier. There is general understanding of the benefits of chlorination in the community but there are not measures that warn the users about biological contamination of the water. Empowering the rural communities in water treatment knowledge and skills, via behaviour changes that include technical training on water quality, cleaning habits and water purification, is a necessity to create awareness at user level. A challenge for effective and sustainable chlorination is the creation of capacities and capabilities at the community level and for local governmental bodies to provide permanent support for sustainability.

Analysing the general status of the chlorination practice in three Latin American countries shows that, although the use of chlorine is widely known and considered a classic disinfection method by health care bodies, its application in households is not necessarily effective. Additionally, monitoring of proper practice is lacking, as well as compliance actions from medium to long-term follow-up in all three countries. There is a need for more research and solutions to address the effective implementation of chlorination at household level, specifically addressing compliance.

This work highlights the challenges associated with the implementation of household-based water treatment interventions and the need for capacity building when introducing interventions in communities and households. It is important to address some factors e.g. by gaining more knowledge on how chlorination is actually practised (dosing and contact time) and the specific water quality (physiochemical and microbial) to customize the dose and avert taste issues by overdosing as well as identifying the potential need for a multi-barrier approach.

Author contributions

Conceptualization, A.M. Nielsen, P. Fernández-Ibáñez and J.A. Byrne; methodology, A.M. Nielsen; supervision, S. Golden, P. Fernández-Ibáñez and J.A. Byrne; writing—original draft preparation, A.M. Nielsen, L.P.S. Paz, L.A.T. Garcia, K.J.S. Silva, M.M. Hincapié Pérez, A. Galdos-Balzategui and F. Reygadas; Supervision; writing—review and editing, S. Golden, P. Fernández-Ibáñez and J.A. Byrne.

Funding

This work was supported by the Global Challenges Research Fund – United Kingdom Research and Innovation (GCRF-UKRI) for SAFEWATER (Grant Ref number EP/P032427/1); The Royal Society (ICA\R1\201373 - International Collaboration Awards, 2020); National Council for Scientific and Technological Development (CNPq-Brazil, process nº 308070/2021–6); DfE Northern Ireland (funding the PhD of A.M. Nielsen); and The Coordination for the Improvement of Higher Education Personnel CAPES-PROEX, financial code 001 (granted K.J.S. Silva with a PhD scholarship).

Declaration of competing interest

The authors declare no conflict of interest.

References

APHA, 2012. In: Rice, E.W., Baird, R.B., Eaton, A.D., Clesceri, L.S. (Eds.), Standard Methods for the Examination of Water and Wastewater, twenty-second ed., American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF) Washington, D.C., USA.
Ávila de Navia, S.L., Estupiñán-Torres, S.M., Díaz González, L., 2016. Bacteriological water quality of the Vereda El Charco, San Miguel de Sema, Boyacá, Colombia (Calidad bacteriológica del agua Vereda El Charco, San Miguel de Sema, Boyacá, Colombia). Nova 14 (25), 139–145.
Blum, A., Null, C., Hoffmann, V., 2014. Marketing household water treatment: willingness to pay results from an experiment in rural Kenya. Water, 6(7), 1873-1886.
Boisson, S., Stevenson, M., Shapiro, L., Kumar, V., Singh, L., Ward, D., Clasen, T., 2013. Effect of household-based drinking water chlorination on diarrhoea among children under five in Orissa, India: a double-blind randomised placebo-controlled trial. PLoS Med. 10 (8), e1001497.
Brazilian Ministry of Health, 2011. Care for water for human consumption (Cuidados com água para consumo humano). Brazilian Ministry of Health. https://bvsms.saude.gov.br/bvs/folder/cuidados_agua_consumo_humano_2011.pdf.
CDC, 2014a. Free Chlorine Testing. https://www.cdc.gov/safewater/chlorine-residual-testing.html. (Accessed 23 October 2019).
CDC, 2014b. Safe Water System. https://www.cdc.gov/safewater/index.html. (Accessed 19 May 2020).
Chankova, S., Hatt, L., Musange, S., 2012. A community-based approach to promote household water treatment in Rwanda. J. Water Health 10 (1), 116–129.
Clasen, T., Edmondson, P., 2006. Sodium dichloroisocyanurate (NaDCC) tablets as an alternative to sodium hypochlorite for the routine treatment of drinking water at the household level. Int. J. Hyg Environ. Health 209 (2), 173–181. https://doi.org/10.1016/j.ijheh.2005.11.004.
Clasen, T., Haller, L., Walker, D., Bartram, J., Cairncross, S., 2007. Cost-effectiveness of water quality interventions for preventing diarrheal disease in developing countries. PLoS Med. 5 (4), 599–608.
COFEPRIS, 2016. https://datos.gob.mx/busca/dataset/calidad-del-agua-de-uso-y-consumo-humano. (Accessed 13 June 2020).
Colombia, 2018. Basic Water and Sanitation Master Plan. Strategic Vision 2018 – 2030 (Plan Director Agua Y Saneamiento Básico. Visión Estratégica 2018 – 2030). Bogotá

D.C., Colombia: Viceministerio de Agua y Saneamiento Básico, Gobierno de Colombia, Minvivienda.
Conagua, 2018. Water statistics in Mexico (Estadisticas del Agua en México). http://sina.conagua.gob.mx/publicaciones/EAM_2018.pdf.
Crump, J., Otieno, P., Slutsker, L., Keswick, B., Rosen, D., Hoekstra, M., Vulule, J.M., Luby, S., 2005. Household based treatment of drinking water with flocculant-disinfectant for preventing diarrhoea in areas with turbid source water in rural western Kenya: cluster randomised controlled trial. BMJ 331, 7515, 478.
De Souza, R.S., De Menezes, L.G., Felizzola, J.F., Figueiredo, R.O., Sá, T.D., Guerra, F.A., 2016. Water and health in igarapé-açu, pará, Brazil. Saúde Soc. 25 (4), 1095–1107.
Deng, Y., 2021. Making waves: principles for the design of sustainable household water treatment. Water Res. 198, 117151.
Embrapa, 2015. Planting Water – Embrapa Chlorinator (Plantando Água – Clorador Embrapa). São Carlos: Embrapa Instrumentação. Brazilian Agricultural Research Corporation. https://www.iniciativaverde.org.br/biblioteca-nossas-publicacoes.php.
Ercumen, A., Naser, A., Unicomb, L., Arnold, B., Colford, J., Luby, S., 2015. Effects of source-versus household contamination of tubewell water on child diarrhea in Rural Bangladesh: a randomized controlled trial. PLoS One 10 (3), e0121907.
Félix-Fuentes, A., Campas-Baypoli, O.N., Aguilar-Apodaca, M.G., Meza-Montenegro, M. M., 2007. Microbiological quality of water for human consumption in three rural communities in southern Sonora (Mexico) (Calidad microbiológica del agua de consumo humano de tres comunidades rurales del sur de Sonora (México)). RESPYN 8 (3), 1–13.
Feng, C., Xu, Z., Li, Y., Zhu, N., Wang, Z., 2021. Research progress on the contamination status and control policy of *Giardia* and *Cryptosporidium* in drinking water. J. Water, Sanit. Hyg. Dev. 11 (6), 867–886.
Ferreira, D.C., Luz, S.L., Buss, D.F., 2016. Evaluation of simple diffusion chlorinators for decontamination of wells in a rural settlement in Amazonia, Brazil. Ciência Saúde Coletiva 21 (3), 767–776.
Firth, J., Balraj, V., Muliyil, J., Roy, S., Rani, L., Chandresekhar, R., Kang, G., 2010. Point-of-use interventions to decrease contamination of drinking water: a randomized, controlled pilot study on efficacy, effectiveness, and acceptability of closed containers, Moringa oleifera, and in-home chlorination in rural South India. Am. J. Trop. Med. Hyg. 82 (5), 759–765.
Freeman, M., Quick, R., Abbott, D., Ogutu, P., Rheingans, R., 2009. Increasing equity of access to point-of-use water treatment products through social marketing and entrepreneurship: a case study in western Kenya. J. Water Health 7 (3), 527–534.
Funasa, 2014. Water chlorination manual in small communities using the simplified chlorinator developed by Funasa (Manual de cloração de água em pequenas comunidades utilizando o clorador simplificado desenvolvido pela Funasa). Brazilian National Health Fundation, Brazil.
Galdos-Balzategui, A., Torre, J.C., Sánchez-Pérez, H., López, J.J., Dosal, A.T., Urbina, S. G., 2017. Quantitative microbial risk assessment of drinking water in San Cristóbal de Las Casas, Chiapas, Mexico (Evaluación cuantitativa del riesgo microbiológico por consumo de agua en San Cristóbal de Las Casas, Chiapas, México). Tecnol. y Cienc. del Agua 8 (1), 133–153.
Gallandat, K., Lantagne, D., 2018. Lessons learned from fifteen drinking water treatment program evaluations in Haiti. Loughborough University. Transformation towards sustainable and resilient WASH services. In: Proceedings of the 41st WEDC International Conference, 2895. WEDC, Loughborough University, United Kingdom.
Garrett, V., Ogutu, P., Mabonga, P., Ombeki, S., Mwaki, A., Aluoch, G., Phelan, M., Quick, R., 2008. Diarrhoea prevention in a high-risk rural Kenyan populationthrough point-of-use chlorination, safe water storage,sanitation, and rainwater harvesting. Epidemiol. Infect. 136 (11), 1463–1471.
GBD, 2018. Causes of Death Collaborators, 2018. Global, regional, and national age-sex-specific mortality for 282 causes of death in 195 countries and territories, 1980–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 392 (10159), 1736–1788.
Gcrf-Ukri, 2020. Safewater project. https://www.safewater-research.com/. (Accessed 24 April 2020).
Geremew, A., Mengistie, B., Mellor, J., Lantagne, D., Alemayehu, E., Sahilu, G., 2019. Consistent point-of-use water chlorination among households using unimproved water sources and treatment preference in Eastern Ethiopia. Int. J. Environ. Health Res. 29 (6), 686–701.
Guerra, C.H., 2006. Evaluation of the Efficiency of the Clorador Simplified for Diffusion in the Disinfection of the Water for Human Consumption in Country Properties in the Basin of the Ribeirão O Laje – Caratinga/MG. Master thesis, Centro universitário de Caratinga, Brazil.
Guzmán, B., Nava, G., Díaz, P., 2015. Quality of water for human consumption and its association with morbimortality in Colombia, 2008-2012 (La calidad del agua para consumo humano y su asociación con la morbimortalidad en Colombia, 2008-2012). Biomedica 35 (2), 177–190.
Haro, J., Nubes, G., Ortiz, J.R., 2012. Sanitary risks in bacteriological quality of water: an evaluation in ten states of the Mexican Republic (Riesgos sanitarios en calidad bacteriológica del agua: una evaluación en diez estados de la república mexicana. Reg. soc. 24 (3), 257–288.
Harshfield, E., Lantagne, D., Turbes, A., Null, C., 2012. Evaluating the sustained health impact of household chlorination of drinking water in rural Haiti. Am. J. Trop. Med. Hyg. 87 (5), 786–795.
INEGI, 2000. https://www.inegi.org.mx/app/buscador/default.html?q=SEG%C3%9AN+FRECUENCIA+DE+RECEPCI%C3%93N+DE+AGUA. (Accessed 13 June 2020).
INEGI, 2018. Cerca de la mitad de los hogares realizan algún tipo de seperación o classificatción d la basura: módulo de hogares y medio ambiente.
Inungu, J., Zinsou, C., Mustafa, Y., Younis, M., Singbo, N., 2016. Factors associated with the uptake of Sodium dichloroisocyanurate (NADCC) tablets as household water-treatment product among caregivers of children under five in Benin, West Africa. J. Health Hum. Serv. Adm. 39 (1), 122–141.
Kumwenda, S., Morse, T.K., Lungu, K.T., Mwendera, C., Kasambara, A., 2014. Household use of water guard for treating drinking water in Chikwawa district, Southern Malawi. Malawi. J. Appl. Sci. 1 (1), 2–9.
Lantagne, D., Clasen, T., 2013. Effective use of household water treatment and safe storage in response to the 2010 Haiti earthquake. Am. J. Trop. Med. Hyg. 89 (3), 426–433.
Lantagne, D.S., Blount, B.C., Cardinali, F., Quick, R., 2008. Disinfection by-product formation and mitigation strategies in point-of-use chlorination of turbid and non-turbid waters in western Kenya. J. Water Health 6 (1), 67–82.
Lantagne, D.S., Cardinali, F., Blount, B.C., 2010. Disinfection by-product formation and mitigation strategies in point-of-use chlorination with sodium dichloroisocyanurate in Tanzania. Am. J. Trop. Med. Hyg. 83 (1), 135–143. https://doi.org/10.4269/ajtmh.2010.09-0431.
Lantagne, D.S., Blanton, E., Kotlarz, N., Gezagehn, H., van Dusen, E., Berens, J., Jellison, K., 2011. Hypochlorite solution expiration and stability in household water treatment in developing countries. J. Environ. Eng. 137 (2), 131–136. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000299.
Levy, K., Anderson, L., Robb, K., Cevallos, W., Trueba, G., Eisenberg, J., 2014. Household effectiveness vs. laboratory efficacy of point-of-use chlorination. Water Res. 54, 69–77.
Loharikar, A., Russo, E., Sheth, A., Menon, M., Kudzala, A., Tauzie, B., Masuku, H.D., Ayers, T., Hoekstra, R.M., Quick, R., 2013. Long-term impact of integration of household water treatment and hygiene promotion with antenatal services on maternal water treatment and hygiene practices in Malawi. Am. J. Trop. Med. Hyg. 88 (2), 267–274.
Makutsa, P., Nzaku, K., Ogutu, P., Barasa, P., Ombeki, S., Mwaki, A., Quick, R., 2001. Challenges in implementing a point-of-use water quality intervention in rural Kenya. Am. J. Publ. Health 91 (10).
Mclaughlin, L., Levy, K., Beck, N., Shin, G., Meschke, J., Eisenberg, J., 2009. An observational study on the effectiveness of point-of-use chlorination. J. Environ. Health 71 (8), 48–53.
Meierhofer, R., Wietlisbach, B., Matiko, C., 2019. Influence of container cleanliness, container disinfection with chlorine, and container handling on recontamination of water collected from a water kiosk in a Kenyan slum. J. Water Health 17 (2), 308–317. https://doi.org/10.2166/wh.2019.282.
Mengistie, B., Berhane, Y., Worku, A., 2013. Household water chlorination reduces incidence of diarrhea among under-five children in rural Ethiopia: a cluster randomized controlled trial. PLoS One 8 (10).
Mitro, B., Wolfe, M., Galeano, M., Sikder, M., Gallandat, K., Lantagne, D., 2019. Barriers and facilitators to chlorine tablet distribution and use in emergencies: a qualitative assessment. Water 11 (6).
Mohamed, H., Brown, J., Njee, R., Clasen, T., Malebo, H., Mbuligwe, S., 2015. Point-of-use chlorination of turbid water: results from a field study in Tanzania. J. Water Health 13 (2), 544–552.
Murray, A., Napotnik, J., Rayner, J., Mendoza, A., Mitro, B., Norville, J., Faith, S.H., Eleveld, A., Jellison, K.L., Lantagne, D., 2020. Evaluation of consistent use, barriers to use, and microbiological effectiveness of three prototype household water treatment technologies in Haiti, Kenya, and Nicaragua. Sci. Total Environ. 718, 134685.
Navarro, I., Jiménez, B., Maya, C., Lucario, E.S., 2007. Assessment of potential cancer risks from THMs in water supply at Mexican rural communities. In: International Symposium on New Directions in Urban Water Management. UNESCO IHP, Paris, France.
Nguyen, K.H., Operario, D.J., Nyathi, M.E., Hill, C.L., Smith, J.A., Guerrant, R.L., Samie, A., Dillingham, R.A., Bessong, P.O., Rogawski McQuade, E.T., 2021. Seasonality of drinking water sources and the impact of drinking water source on enteric infections among children in Limpopo, South Africa. Int. J. Hyg Environ. Health 231, 113640.
Opryszko, M., Majeed, S., Hansen, P., Myers, J., Baba, D., Thompson, R., Burnham, G., 2010. Water and hygiene interventions to reduce diarrhoea in rural Afghanistan: a randomized controlled study. J. Water Health 8 (4), 687–702.
Parker, A., Stephenson, R., Riley, P., Ombeki, S., Komolleh, C., Sibley, L., Quick, R., 2006. Sustained high levels of stored drinking water treatment and retention of hand-washing knowledge in rural Kenyan households following a clinic-based intervention. Epidemiol. Infect. 134 (5), 1029–1036.
Parvez, S.M., Azad, R., Rahman, M., Unicomb, L., Ram, P., Naser, A., Stewart, C.P., Jannat, K., Rahman, M.J., Leontsini, E., Winch, P.J., Luby, S., 2018. Achieving optimal technology and behavioral uptake of single and combined interventions of water, sanitation hygiene and nutrition, in an efficacy trial (WASH benefits) in rural Banglades. Trials 19, 358.
Patrick, M., Berendes, D., Murphy, J., Bertrand, F., Husain, F., Handzel, T., 2013. Access to safe water in rural artibonite, Haiti 16 Months after the onset of the cholera epidemic. Am. J. Trop. Med. Hyg. 89 (4), 647–653.
Peres, M.R., Ebdon, J., Purnell, S., Taylor, H., 2020. Potential microbial transmission pathways in rural communities using multiple alternative water sources in semi-arid Brazil. Int. J. Hyg Environ. Health 224, 113431.
Quiroga, E., García, M., Solarte, Y., 2015. Community participation: a strategy to achieve low-risk microbiological water and effective disinfection (Participación comunitaria: Una estrategia para lograr agua de bajo riesgo microbiológica y una desinfección efectiva).
Ram, P., Kelsey, E., Rasoatiana, M.R., Rakotomalala, O., Dunston, C., Quick, R., 2007. Bringing safe water to remote populations: an evaluation of a portable point-of-use intervention in rural Madagascar. Am. J. Publ. Health 97 (3), 398–400.

Rangel, J., Lopez, B., Mejia, M., Mendoza, C., Luby, S., 2003. A novel technology to improve drinking water quality: a microbiological evaluation of in-home flocculation and chlorination in rural Guatemala. J. Water Health 1 (1), 15–22.
RAS, 2010. Technical Regulation for the Drinking Water and Basic Sanitation Sector-RAS (Reglamento Técnico para el Sector de Agua Potable y Saneamiento Básico-RAS). República de Colombia. Ministerio de Vivienda, Ciudad y Territorio.
Ribeiro, M.R., de Abreu, L.C., Laporta, G.Z., 2018. Drinking water and rural schools in the Western Amazon: an environmental intervention study. PeerJ 15 (6), e4993.
Ritter, M., Camille, E., Velcine, C., Guillaume, R., Lantagne, D., 2017. Optimizing household chlorination marketing strategies: a randomized controlled trial on the effect of price and promotion on adoption in Haiti. Am. J. Trop. Med. Hyg. 97 (1), 271–280.
Rodrigues, M.E., 2013. Water treatment: Tablet chlorinator (Tratamento de água: clorador de Pastilha). Belo Horizonte: Emater-MG.
Roma, E., Bond, T., Jeffrey, P., 2014. Factors involved in sustained use of point-of-use water disinfection methods: a field study from Flores Island, Indonesia. J. Water Health 12 (3), 573–583.
Rosa, G., Kelly, P., Clasen, T., 2016. Consistency of use and effectiveness of household water treatment practices among urban and rural populations claiming to treat their drinking water at home: a case study in Zambia. Am. J. Trop. Med. Hyg. 94 (2), 445–455.
Rubino, F., Corona, Y., Pérez, J.G., Smith, C., 2019. Bacterial contamination of drinking water in Guadalajara, Mexico. Int. J. Environ. Res. Publ. Health 16 (1), 67.
Sánchez, L., Rodríguez, S., Escobar, J., Torres, P., 2010. Modeling of residual chlorine and disinfection by-products in a pilot sector of the drinking water distribution system in the city of Cali. Inycompe 12 (1), 127–138.
Soares, D., 2007. Access, supply and control of water in an indigenous Chamula community in Chiapas. An analysis from the perspective of gender, environment and development. Reg. soc. 19 (38), 25–50.
Solomon, E., Robele, S., Kloos, H., Mengistie, B., 2020. Effect of household water treatment with chlorine on diarrhea among children under the age of five years in rural areas of Dire Dawa, eastern Ethiopia: a cluster randomized controlled trial. Infect. Dis. Poverty 9 (1), 64.
Solomon, E., Robele, S., Kloos, H., Mengistie, B., 2021. Comparing the effect of independent and combined interventions of household chlorination and handwashing on diarrhea of under-fives in rural Dire Dawa, eastern Ethiopia: a cluster randomized controlled trial. Pan. Afr. Med. J. 40, 239.
Tvrdá, E., Benko, F., 2020. Chapter 1 - free radicals: what they are and what they do. In: Preedy, V.R. (Ed.), Pathology. Academic Press, ISBN 9780128159729, pp. 3–13.
USEPA, 1999. Alternative Disinfectants and Oxidants Guidance Manual. USEPA.
Vásquez, W.F., Mozumder, P., Hernández-Arce, J., Berrens, R.P., 2009. Willingness to pay for safe drinking water: evidence from Parral, Mexico. J. Environ. Manag. 90 (11), 3391–3400.
Wheeler, J., Agha, S., 2013. Use of Certeza point-of-use water treatment product in Mozambique. J. Water, Sanit. Hyg. Dev. 3 (3), 341–348.
WHO, 2011. Evaluating Household Water Treatment Options: Health-Based Targets and Microbiological Performance Specifications. WHO, Geneva.
WHO, 2017. Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum. World Health Organization, Geneva. Licence: CC BY-NC-SA 3.0 IGO.
WHO, 2019. Results of Round II of the WHO Household Water Treatment Evaluation Scheme. WHO, Geneva.
WHO, 2021. Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020: Five Years into the SDGs. WHO, Geneva.
WHO and UNICEF, 2012. A Toolkit for Monitoring and Evaluating Household Water Treatment and Safe Storage Programmes. UNICEF and WHO, Geneva.
WHO and UNICEF, 2017. Progress on Drinking Water, Sanitation, and Hygiene: 2017 Update and SDG Baselines. UNICEF and WHO, Geneva.
WHO and UNICEF, 2020. https://washdata.org/data/household#!/dashboard/3002. (Accessed 21 April 2020).
Wilhelm, N., Kaufmann, A., Blanton, E., Lantagne, D., 2018. Sodium hypochlorite dosage for household and emergency water treatment: updated recommendations. J. Water Health 16 (1), 112–125. https://doi.org/10.2166/wh.2017.012.
Wood, S., Foster, J., Kols, A., 2012. Understanding why women adopt and sustain home water treatment: insights from the Malawi antenatal care program. Soc. Sci. Med. 75 (4), 634–642.
Xavier, R.P., Siqueira, L.P., Vital, F.A., Rocha, F.J., I, J., Calazans, G.M., 2011. Microbiological quality of drinking rainwater in the inland region of Pajeú, Pernambuco, Northeast Brazil. Rev. Inst. Med. Trop. Sao Paulo 53 (3), 121–124.
Xiao, R., Duan, Y., Chu, W., 2020. The effectiveness of household water treatment and safe storage in improving drinking water quality: a disinfection by-product (DBP) perspective. J. Water Supply Res. Technol. - Aqua 69 (8), 785–806.