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IS CHLORINATION THE RIGHT SOLUTION FOR HOUSEHOLD WATER DISINFECTION IN INDONESIA? A CRITICAL REVIEW

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ABSTRACT

Chlorination is one of the household water treatment methods widely advocated in Indonesia. Challenges to effectiveness and efficiency, however, persist. This study reviews literature related to chlorination practices, with emphasis on the factors affecting successful practice and potential points at which improvements may be initiated. We discuss how water quality can affect chlorine effectiveness, the need for dosing strategies that correspond with the source water quality, optimization tests of disinfection processes, and possible disinfection by-products. This review also explores alternative disinfection methods, such as filtration, UV irradiation, and boiling, comparing their advantages and disadvantages. User compliance is necessary but, in most cases, compromised by lack of motivation, misconceptions regarding chlorine safety, and perceived inconvenience. Specifically, this review identifies several key research gaps, including the need for further investigation into the long-term impacts of household chlorination on user behavior and the effectiveness of various communication strategies in promoting sustained adoption. We examine barriers and drivers to successful implementation in an Indonesian context considering all the factors influencing awareness, access, affordability, cultural practices, and government policies. We realize that these guidelines may not be enough to satisfactorily adopt chlorination, hence a call to focus our effort on the local environment with continued support toward behavior change. Based on our review, we include recommendations to further enhance efficiency, compliance, and sustainability in Indonesia's household chlorination programs and thus reduce disparity in access to safe drinking water as a means to improve the public health conditions.

Keywords: Chlorination, Household Water Treatment (HWT), Drinking water, Water quality, Public health, Indonesia.

Abbreviation

CD	Chlorine Demand
DBPs	Disinfection By-Products
FC	Free Chlorine
FCR	Free Chlorine Residual
HWT	Household Water Treatment
NaDCC	Sodium Dichloroisocyanurate
NaClO	Sodium Hypochlorite
NOM	Natural Organic Matter
PAMSIMAS	the name of a community-based water supply and sanitation program in Indonesia
POU	Point-of-Use
THMs	Trihalomethanes
WASH	Water, Sanitation, and Hygiene

INTRODUCTION

Water has become a critical global concern, encompassing both quantitative scarcity and qualitative degradation, though its manifestations vary regionally. A series of comprehensive reports have consistently identified the principal drivers as follows: (i) rapid population growth, which intensifies demand; (ii) pollution arising from mining operations and industrial processing; and (iii) climate change, which disrupts the global hydrological cycle (Aroua, 2023). The water issue is also an energy challenge because, for a given country or region, water and energy are both essential for sustainable development (Boubou-Bouziani, 2015).

The access to safe and affordable drinking water is a fundamental human right integral to the Sustainable Development Goals formulated by the United Nations (UN, 2021). Despite increased focus on realizing this human right, 1.7 billion people still lacked safely managed drinking water in 2020 (WHO, 2023). The burden of this challenge disproportionately affects rural communities in low-income countries, where reliance on contaminated and distant water sources remains prevalent. In Indonesia, despite progress in water supply coverage, access to safe drinking water remains a challenge, particularly in rural areas and small towns. The 2023 Indonesia National Socio-Economic Survey indicates that only 12.17% of households have access to piped water treated to drinking water quality standards (Indonesia Central Agency of Statistics, 2024).

The global water stress context urgently calls for the promotion of nonconventional water resources, including purified wastewater, to save the maximum volume of conventional water resources, as stated in Sustainable Development Goal 6, clean water and sanitation (Aroua-Berkat and Aroua, 2022).

Consumption of unsafe drinking water can lead to significant health issues and mortality due to enteric infections, especially among children (Faye, 2017; Baba Hamed, 2021; Lee et al., 2023). The leading causes of death from diarrheal diseases are pathogens such as rotavirus, Cryptosporidium, and Salmonella (Black et al., 2022). These are primarily transmitted through the fecal-oral route and associated with unsafe drinking water, poor sanitation, and hygiene. For these reasons, it is imperative that bacteriological analyses of the water be conducted with the utmost rigor, concurrently with the monitoring of residual chlorine levels (Ouahchia et al., 2015). Statistical analysis methods should be privileged (Diallo et al., 2014; Amadou et al., 2014).

In Indonesia, diarrheal diseases remain a significant public health concern, particularly among children under five. The Ministry of Health reported that diarrhea was the second leading cause of infant mortality in 2021 (IMH, 2023).

Phosphorus in the form PO_4^{3-} and Nitrogen, particularly in the form of nitrates (NO_3^-) and nitrites (NO_2^-), ares commonly found in water sources, especially in areas influenced by agriculture or wastewater discharge. These are highly harmful elements that several studies have been carried out to provide processes eliminating them or at least reduce them to an authorized concentration (Mumthaj et al., 2023; Aw et al., 2024).

Furthermore, monitoring the chemical and bacteriological quality of stored drinking water is essential to prevent population health risks (Douhri et al., 2015). The drinking water quality that is being supplied to people through the water supply system has a direct impact on public health (WHO, 2022). Thus, the optimum use of water requires an effective water supply management system that is smart enough to measure water quality and produce details for the end user (Pandey et al., 2022; Kouloughli and Telli, 2023).

As a general rule, water pollution presents a considerable ecological hazard, especially in rapidly industrializing areas. Several studies have been carrried out to examine deficiencies in health risk assessment and pollutant source identification in such regions (Tanouayi et al., 2015; Benhamza et al., 2015; Chadee et al., 2024).

Assessing water quality is essential for several reasons, and it directly impacts public health, the environment, and economic development. Best methods should be preferred to assess water quality, such as integrated methods (Sahu et al., 2024).

Household water treatment (HWT), where water is treated at the point of use (POU), can be a crucial solution to help address these issues, especially where centralized solutions are not feasible due to high costs, maintenance needs, or the dispersed nature of households (Bielefeldt, 2010). Although many different technologies are available and have the potential to provide safe drinking water, they face the challenge of low effectiveness and compliance in the field (Deng, 2021). This is a critical gap in research, as little is known about the actual circumstances under which these methods are performed.

Chlorination has been used as a disinfectant since the early 1900s (Reddy and Elias), and in tropical countries, it is the most common and cost-effective method at the household water level, or other water storage structures, compared to filtration, solar disinfection, and combined flocculation/disinfection (Harrat and Achour, 2010; Achour and Chabbi, 2014: Mazhar et al., 2020). This holds true in Indonesia, where chlorination is widely promoted as a key HWT method. Among the methods mentioned, only chlorination and combined flocculation/disinfection provide the residual disinfectant required to protect water quality during household water storage, where recontamination risks exist (Said, 2017). Here, chlorination has a clear advantage over combined flocculation/disinfection as it is cheaper and easier to perform (Afoufou and Achour, 2002; Afoufou and Achour, 2003; Achour et al., 2002; Ghernaout, 2018). Besides chlorination, other methods are also used for drinking water disinfection at the household level, such as filtration, UV irradiation, heating to a boil, and ozonation which is known to be a powerful oxidant and disinfectant in drinking water production processes, providing provided that the optimal dose is planned (Hellal et al., 2023). These methods each have advantages and disadvantages in terms of effectiveness, cost, and ease of implementation.

At the household level, chlorination can be easily applied by adding a specific dose of household bleach, a sodium hypochlorite solution ($NaClO$), and is one of the most accessible methods, as $NaClO$ is widely produced and sold. An alternative to $NaOCl$ is sodium dichloroisocyanurate (NaDCC), which has the advantages of being more stable in storage, safer, and more convenient (Agrawal and Bhalwar, 2009; Clasen and Edmondson, 2006; Wilhelm et al., 2018). However, the impact of the chlorination process on the substances contained in the water must be monitored (Khelili and Achour, 2017).

When chlorine is added to water, either in molecular or hypochlorite form, it undergoes hydrolysis to produce aquatic chlorine molecules, hypochlorous acid ($HClO$), and hypochlorite ions (ClO^-). Together, they are known as free chlorine (FC) (Gohil and Suresh, 2017). Both chlorine compounds are antimicrobial agents, but hypochlorous acid is significantly more effective than hypochlorite ions (Almhöjd et al., 2023). Free chlorine can eliminate various bacteria and viruses found in contaminated drinking water. However, it is less effective against protozoa, especially at concentrations safe for drinking water (He et al., 2023).

Although chlorination is a simple method to treat contaminated water, it faces several challenges for effective implementation, especially in rural areas of Indonesia. This review aims to critically examine and analyze scientific and non-scientific literature on chlorination in practice to identify the main challenges and research gaps associated with the scaling up, adoption, compliance, effectiveness, and sustainability of household water chlorination in real-world scenarios. Particular attention is given to the identified key barriers and drivers for adequate implementation in Indonesia, and supporting case studies are discussed.

METHODS

A comprehensive literature review was conducted to examine household chlorination practices in rural Indonesia. The initial search across multiple databases (Scopus, Web of Science, Directory of Open Access Journals, Garuda, and Google Scholar) using relevant keywords yielded over 1100 manuscripts. Keywords used in the search included terms related to chlorination methods (e.g., disinfect*, chlorin*, hypochlorite, "sodium dichloroisocyanurate", NaDCC, bleach), water treatment (e.g., "drinking water", potable, "water treat*", household, HWT, "household water treatment", "Safe water system", SWS, "point-of-use", POU), and setting (e.g., Indonesia, rural*, communit*, "field trial", intervention, "field implementation", "field implementing", "developing countr*", LMIC, "low and middle-income country"). Titles and abstracts were screened to identify studies specifically focused on chlorination in rural Indonesian communities, excluding laboratory-based research, review papers, publications not in English or Indonesian, and duplicate documents. This screening process narrowed down the pool to 217 articles. After reviewing the abstracts, fewer than 90 articles were selected for full-text analysis. Final inclusion in the review was based on relevance to the topic of household chlorination in rural Indonesia. This therefore ensured that only literature that was very relevant and informative on the subject was reviewed.

RESULTS AND DISCUSSIONS

Issues with chlorination

Challenges in chlorination related to source water quality, dosage, and storage

The efficacy of chlorination in rendering drinking water free from harmful microorganisms relies immensely on source water quality. The dosing and time of chlorine required for satisfactory disinfection could be impacted by factors related to turbidity, pH, and temperature conditions, as well as the content of organic matter, or humic matter, within the water (Achour et al., 2002; Khelili and Achour, 2015; Aw et al., 2016; Achour et al., 2016; Achour et al., 2018; Mazhar et al., 2020; Mohseni et al., 2017).

In Indonesia, where water sources can be quite different, from relatively clean springs in mountainous regions to heavily polluted rivers in densely populated areas, and from groundwater with high mineral content to rainwater harvesting systems, it is important to define the appropriate dosage of chlorine depending on the source (Wantasen et al., 2022).

- Turbidity: High turbidity can shield pathogens from chlorine, requiring higher doses or pre-treatment like filtration to improve disinfection efficacy (Léziart et al., 2019; Benamara and Benamara, 2022). This is particularly relevant in Indonesia, where many rural communities rely on surface water sources prone to high turbidity, especially during the monsoon season (November to April), when heavy rainfall can lead to significant runoff and sediment transport. (Messakh and Punuf, 2020). Besides, improper land use practices, for instance, deforestation and unproper agriculture, contribute to erosion and give rise to high turbidity levels in water bodies.

- pH: Chlorine is most effective in a pH range between 6.5 and 7.5. At higher pH values, the disinfection potential is reduced because less HOCl will be produced, according to Lee and Lee (2015). This may be of concern in Indonesia, as many water sources are naturally at higher levels of pH, especially those derived directly from volcanic regions or carrying agricultural runoff.
- Temperature: This could be a concern in Indonesia, where many water sources may naturally possess higher levels of pH, such as those emanating directly from volcanic regions or those receiving runoff from fertilized farms (Lee and Lee, 2015). One critical factor is the tropical climate of Indonesia. In this country, for most of the year, the ambient temperature remains high and often rises above 30 °C. This high temperature can lead to rapid chlorine decay, especially in open storage containers, further complicating the maintenance of adequate residual chlorine levels.
- Organic Matter: Organic matter in water reacts with chlorine, forming disinfection by-products (DBPs) like trihalomethanes (THMs), some of which are linked to potential health risks (Xiao et al., 2024). High organic content necessitates increased chlorine doses, potentially elevating DBP formation. That has raised a concern in Indonesia due to the prevalent practices in the country, which expose sources of water through the inappropriate disposal of organic wastes and the lack of modern sewage treatment facilities; discharge into water bodies from both untreated domestic and industrial wastes remains common. The same applies to the very informal urban settlements and high population in urban areas.

HWT systems should be capable of purifying water of various microbiological and physicochemical qualities. When chlorine is dosed into the water, it immediately starts reacting with organic matter, metals, and other constituents to reduce its disinfecting potential. The difference between the amount of chlorine added and the free chlorine residual remaining after some contact time is defined as the chlorine demand. This CD depends on various parameters such as temperature, pH, turbidity, and the chemical composition of the water and is specific to a given water source, making it prone to temporal variations (WHO, 2019). This highlights the importance of more in-depth knowledge of water quality over greater time scales, especially in Indonesia, where seasonal variations and dynamic environmental conditions can significantly influence water quality parameters.

Pilot studies were conducted by Kim et al. (2014), Nouiri (2017), and Solomon et al. (2020) on chlorine dosing (CD) in water to find out the optimum chlorine dose in respect of the relationship between water quality and CD. These studies were done in a particular context and might not apply directly to Indonesia because of the diversity of conditions. There is a need for more localized research in terms of finding the appropriate dosage of chlorine in different water sources and communities, each having unique characteristics.

Several studies report the relationship of turbidity and CD of water. Examples include works by Léziart et al. (2019) and Mohamed et al. (2015). In fact, very recent recommendations of chlorine dose by Wilhelm et al. (2018) as listed in Table 1, have been obtained from tests performed with several water sources which had presented different turbidities. Turbidity imparts CD due to the reaction of chlorine with organic and inorganic compounds present in the water. However, some natural organic matter present in water is dissolved and thus not represented by the turbidity level. This is rarely taken into consideration in determining dosage of chlorine in a batch process; this may lead to under-chlorination and thus poor disinfection, especially in Indonesian water sources, which have a high dissolved organic content.

Table 1: Guidelines for chlorine application and residual maintenance in drinking water

Applied dose/FCR	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)
FCR after 30 min	≤0.50 (WHO, 2011)
FCR after 24 h	>0.20 (WHO, 2011)

Besides the challenges with dosing, the storage of chlorinated water is another significant factor in ensuring residual disinfection and preventing recontamination. However, chlorine dissipates over time, especially when exposed to sunlight and heat (Kwio-Tamale and Onyutha, 2024; Noh et al., 2016). This becomes a challenge in Indonesia, since most households store drinking water in containers that are probably not well protected against sunlight and high temperatures (Ikhsan et al., 2022). Traditional practices in the form of storing water in earthenware jars or plastic containers facing direct sunlight can speed up chlorine decay. In addition, using contaminated cups or washing hands in storage containers is very common in Indonesia; these factors introduce new contaminants, rendering positive chlorination useless (Daniel et al., 2023; Puspita et al., 2023).

The WHO realizes that chlorine dosages must be site-specific since site conditions vary. Thus, the WHO guidelines are based on the free chlorine residual (FCR) levels set out in Table 1 below. Based on health reasons, the WHO further advises that FCR should not exceed 5.0 mg/L (WHO, 2011). The literature recommends FCR concentrations in the range 0.2–0.5 mg/L for water to protect against regrowth and recontamination during storage and usage. In reality, however, recommended levels in this range can promote bacterial growth. Meierhofer et al. (2019) concluded that safely chlorinated water from a water kiosk with an average FCR of 0.39 mg/L was not enough to maintain drinking water quality after 24 h of storage when filled into uncleaned jerry cans and used in households in Kenya. The exerted CD was contributed by the uncleaned jerry cans, reducing FCR to an average concentration of 0.19 mg/L. This led to contamination at the point of storage; 15.2% of household stored water had E. coli after 24 h of storage, and a higher dose of chlorine was required to maintain levels of FCR in the water. The same issues could be present in Indonesia, where there is a prevalence of reusing containers without cleaning them properly and dipping contaminated utensils into the stored water.

Pathogens, dosage, and contact time

Chlorine's efficacy in disinfecting drinking water is dependent not only on the water quality but also on the specific types of pathogens present and the contact time between the chlorine and the water. Different pathogens exhibit varying levels of resistance to chlorine disinfection.

The efficiencies, largely dependent on dosage and time of contact. A dosage of a few mg/liter free chlorine with exposure times of even 30-60 min has variously achieved inactivation against all waterborne pathogens at or exceeding levels of 4-log-99.99% of the original microbial load in a sample being killed-by Lanrewaju et al. (2022), and Lu and Zhang (2022). This means that, for instance, if there were an initial sample water containing 10,000 pathogenic organisms per liter, appropriate dose and contact time in chlorination should leave less than 1 viable organism per liter in the treated water. This level of inactivation will generally be adequate to ensure drinking water is safe from microbiological standpoint.

However, a number of pathogens are resistant to chlorination, and this greatly affects the concentration and contact time that may be required to achieve adequate inactivation (Clasen and Edmondson, 2006). Resistance in such cases depends on several factors, for example, the structural properties of the microorganisms themselves, the capability to form resistant stages or spores, and general mechanisms of protection against oxidative stress (Wang et al., 2023; Zhou et al., 2024).

In Indonesia, where waterborne diseases such as typhoid, cholera, and amoebiasis remain significant public health concerns, the effectiveness of chlorination in inactivating these specific pathogens is crucial. Pathogens like the protist Cryptosporidium parvum, for example, are highly resistant to conventional chlorination due to the production of resistant oocysts during its life cycle (Feng et al., 2021). Oocysts are thick-walled, environmentally resistant structures that can survive for extended periods in water and are highly resistant to chlorine disinfection. Generally, higher chlorine concentrations, possibly along with longer contact times than are usually practical in a household water treatment, might be required to adequately inactivate Cryptosporidium oocysts (Jain et al., 2019). This is of special relevance in Indonesia since Cryptosporidium has been identified as one of the common causes of diarrheal illness, particularly in children (Wijayanti, 2017).

Household scale, therefore, under less controlled conditions, for example, than those at water treatment plants, studies such as those done by Levy et al. (2014) had significantly reduced efficiency when compared to laboratory testing. This is for the following reasons:

- Poor user compliance: Inconsistent or inappropriate application of chlorine due to lack of knowledge, motivation, or access to appropriate resources may result in poor disinfection. This is a potential challenge in Indonesia, where health literacy levels and awareness of safe water practices may vary across different communities.

- Recontamination after Storage: If the water treated is stored in contaminated containers or even exposed to other external sources of contamination, the effectiveness of chlorination becomes nullified. In Indonesia, this can well be a problem since most of the traditional methods for water storage, like storing in earthenware jars or uncovered containers, contribute to recontamination.
- High chlorine demand: Organic matter or other chlorine-consuming substances in the water may be so high that it depletes the chlorine residual, and thus there is not enough disinfection and regrowth of microorganisms may occur. This problem is quite common in Indonesia, as many water sources, especially surface waters, are heavily polluted with organic matter due to inadequate sanitation and wastewater management.

Although chlorination is supported by leading organizations such as UNICEF (Mohamed et al., 2015), the fact that it is ineffective against some protozoa means that chlorination products can only obtain limited protection-a '1-star' classification-as reflected in the WHO Household Water Treatment and Safe Storage Evaluation Scheme (WHO, 2011). This classification scheme classifies water treatment technologies based on their capability to remove or inactivate microbial contaminants. 1-star' rating, meaning chlorination alone may not be sufficient to ensure that all of the pathogens are removed, particularly protozoa like Cryptosporidium.

Based on this, WHO recommends that chlorination be used only in situations where the disease-causing pathogens are known or as part of a multi-barrier treatment approach (WHO, 2019). A multi-barrier approach combines multiple water treatment methods to achieve a higher level of protection. For example, combining chlorination with filtration or solar disinfection can enhance the removal of both bacteria and protozoa, providing safer drinking water (Xie et al., 2023). This might find particular relevance in Indonesia due to the various sources of water and diverse types of pathogens, requiring more profound approaches to treatment (Ihsan and Derosya, 2024).

Rajasingham et al. (2019) have effectively applied chlorination in responding to cholera outbreaks during emergency situations. In such a situation, where rapid control of cholera spread is important, chlorination can be a strong tool in disinfecting water sources and hence preventing further transmission. Indonesia has faced several outbreaks of cholera in these recent years, which points to effective strategies of water treatment in emergencies (Praja et al., 2023). However, since the scope of this review does not include the emergency response by chlorination.

Chlorine stability

Stability of chlorine in solution determines the effectiveness of chlorination in household water treatment. Chlorine, in its several forms used for disinfection, is easily degraded, leading to the loss of its effectiveness through various environmental factors Gallandat et al. (2021) indicated that under tropical conditions, with high intensities of sunlight and ambient air temperatures commonly surpassing 30°C-for example, in Indonesia-this presents highly challenging conditions to maintaining the stability of chlorine. Ultraviolet radiation from the sun can readily decompose free chlorine; this process reduces its concentration and, in turn, decreases its disinfection power. This is particularly a major concern in Indonesia, considering that most communities, particularly in rural areas, still do not have access to electricity and thus rely mostly on daylight hours for their daily activities, which eventually increases the chances of being exposed to sunlight. It therefore increases at higher temperatures; for this reason, a relatively high amount of chlorine loss may happen in storage. High intensities of sunlight and corresponding high temperatures require careful storage practices, the possible application of chlorine stabilizers being an integral consideration toward ensuring the desired levels of disinfection.

It is to be noted that the forms of free chlorine, such as hypochlorous acid and hypochlorite ion, depend on the pH of the water. HOCl is more effective as a disinfectant, and its proportion decreases with increased pH, thus affecting the overall disinfection efficacy and stability of chlorine (Dewangan et al., 2023). Furthermore, organic matter and salts in water reacts with chlorine, consuming it and reducing its availability for disinfection (Achour and Guergazi, 2003; Hellal and Achour, 2016; How et al., 2017). This is a significant issue in Indonesia, where many water sources, particularly surface waters and shallow wells, are often contaminated with organic matter due to factors such as open defecation, inadequate wastewater treatment, and agricultural runoff (Wulandari et al., 2024). The high organic content in these water sources also increases chlorine demand, which by itself compromises its stability. This calls for higher doses initially for effective disinfection.

Another critical factor that will affect the stability of chlorine concerns the product itself-the disinfectant. The access to quality-controlled chlorine products is very limited in most rural settings in Indonesia. It is influenced by factors like those of the initial chlorine concentration, availability of stabilizers, and mode of processing. Lantagne et al. (2011) investigated the stability of hypochlorite solutions, which generally stable for as long as 19 months but were found to be drastically reduced in concentration after direct sunlight exposure. This finding suggests that good storage practices will be very important in Indonesia, as the traditional water storage systems include earthenware jars and uncovered containers placed in direct sunlight. Their study also showed that there were variations in the quality and stability of hypochlorite solutions, some of which had a chlorine concentration much lower than expected. This may show serious risks of improper dosing in Indonesia, where chlorine product qualities can vary and household usages or expiration dates are not always followed.

These success stories have made the stability of chlorine solution paramount in Indonesian household water treatment. A variety of conditions related to storage, transport, and accessibility of information for proper handling and utilization pre- and post-application determine its stability and effectiveness as a disinfectant to safely provide drinking water. There is most definitely a need for public education campaigns and community involvement to raise awareness and stimulate proper practices in optimizing benefits from chlorination.

Comparison with alternative household water disinfection methods

While this review focuses on chlorination, it is essential to acknowledge the existence of alternative household water treatment and disinfection methods, each with its own set of advantages and disadvantages. These alternatives include:

1. Filtration

Various filtration technologies, such as ceramic filters, biosand filters, and membrane filters, are available for household use. These filters can effectively remove suspended solids, bacteria, and protozoa, but their efficacy in removing viruses may vary depending on the filter type and pore size (Dandadzi and Kothurkar, 2023). However, filtration is used for all waters regardless of their nature (Awang Nasrizal et al., 2023).

2. UV irradiation

Ultraviolet (UV) irradiation can inactivate a wide range of pathogens, including bacteria, viruses, and protozoa. However, the effectiveness of UV treatment can be affected by water turbidity and the presence of dissolved organic matter, which can absorb UV light and reduce its disinfecting power (Ashok and Khedikar, 2016).

3. Solar disinfection

Solar disinfection, also known as SODIS, involves exposing water to sunlight in clear plastic bottles for several hours. This method can effectively inactivate bacteria and viruses, but its efficacy against protozoa is limited (Burch and Thomas, 1998). Water production is also possible through the use of solar-based methods, such as solar distillation. It is especially recommended for isolated and remote areas (Zioui et al., 2015).

4. Boiling

Heating water to a rolling boil for one minute can effectively kill most harmful pathogens. However, boiling requires a reliable source of fuel or electricity, which may not be readily available in all communities (Nicole, 2021).

To provide a clearer comparison of these methods, Table 2 summarizes the effectiveness, cost, ease of use, sustainability, and user acceptance of each method, including chlorination.

Table 2: Comparing Chlorination with Alternatives

Feature	Chlorination	Filtration	UV Irradiation	Solar Disinfection	Boiling
Effectiveness	Effective against bacteria and viruses, less effective against some protozoa	Effective against bacteria and protozoa, efficacy against viruses varies	Effective against a wide range of pathogens	Effective against bacteria and viruses, less effective against protozoa	Effective against most pathogens
Cost	Low	Moderate to high (depending on filter type)	Moderate to high (depending on system)	Low	Moderate (depending on fuel source)
Ease of Use	Simple to use, requires correct dosage and contact time	Simple to use, requires regular cleaning and maintenance	Requires electricity or batteries	Requires sunlight and exposure time	Requires fuel or electricity
Sustainability	Requires continuous supply of chlorine	Requires filter replacement or regeneration	Requires electricity or batteries	Requires sunlight and plastic bottles	Requires fuel or electricity
User Acceptance	Can be affected by taste and odor issues	Generally, well accepted	Generally, well accepted	Generally, well accepted	Generally, well accepted

The choice of the most appropriate household, even drinking water, disinfection method depends on various factors, including the specific context, water quality, pathogen risks, user preferences, and resource availability (Gaouar and Gaouar, 2016; Achour and Chabbi, 2017; Yadav et al., 2024). In Indonesia, where water quality varies significantly and access to resources may be limited, a combination of methods or a multi-barrier approach may be most effective in ensuring safe drinking water.

In addition to the methods mentioned above, the USEPA (1999) provides a comprehensive guidance manual on alternative disinfectants and oxidants for water treatment. This manual explores a range of options, including ozone, chlorine dioxide, and chloramines, each with its own set of advantages and disadvantages in terms of effectiveness, cost, and potential by-products. The USEPA manual also provides guidance on the selection and implementation of appropriate disinfection methods based on site-specific conditions, such as water quality and pathogen risks.

For larger-scale water treatment systems, advanced oxidation processes (AOPs) may be more suitable. AOPs involve the generation of highly reactive hydroxyl radicals, which can effectively degrade a wide range of organic pollutants and inactivate pathogens (Priyadarshini et al., 2022). However, AOPs typically require specialized equipment and expertise, making them less practical for household-level implementation. Further research could explore the potential of AOPs for community-level water treatment systems in Indonesia, particularly in areas with high levels of contamination or limited access to conventional treatment methods.

Disinfection By-Products

While chlorination effectively disinfects drinking water, it can also lead to the formation of disinfection by-products (DBPs) (Hellal and Achour, 2016). These unwanted chemical compounds are formed when chlorine reacts with natural organic matter (NOM) and other precursors like bromide and iodide in the water (Mazhar et al., 2020; Xiao et al., 2024). Some DBPs have been related to possible health risks; hence, a long-term consumption of chlorinated drinking water is raised as a concern (Mishra et al., 2014). This issue has been so relevant in Indonesia due to natural water sources (surface waters and shallow wells) which have a high content of NOM as the consequence of heavy agricultural runoff, poor treatment of wastewater, and certain areas having a population that is highly condensed. High temperatures and strong sunlight in Indonesia's tropical climate increase the potential formation of DBPs by the fast reaction between chlorine and NOM.

Many different kinds of DBPs can be formed during chlorination, and some might pose health risks. Water quality, contact time, temperature, and pH are important factors affecting the type and amount of DBPs formed in the process (Doederer et al., 2014; Xiao et al., 2024). On the other hand, Indonesian studies also indicated that close to field conditions, DBPs would not significantly exceed WHO guideline values for drinking water, even with high-turbidity water (Kalita et al., 2024). It also insinuates from this that generally, risks of DBPs could be managed with effective chlorination practices and proper monitoring.

These findings notwithstanding, the concern about DBP formation and possible health effects can still be a limiting factor in user compliance. In Indonesia, where knowledge on DBPs and possible health implications may be limited, public education and communication of such fears are very important in promoting widespread acceptance and appropriate usage of chlorination for household water treatment.

According to Xiao et al. (2020), DBPs usually occur in drinking water at sub-$\mu g \cdot L^{-1}$ or low to moderate $\mu g \cdot L^{-1}$ concentrations. In Indonesia, due to the widespread practice of point-of-use water treatment, encouraging easy and inexpensive approaches that can be implemented at household scales to reduce NOM concentrations prior to chlorination-for example, using a simple cloth filter or simply settling the water-can often sufficiently minimize DBP production.

When DBPs do occur, their removal-activated carbon adsorption of organic compounds following disinfection-typically becomes necessary (Ma et al., 2016). However, other domestic water treatment options such as the removal of volatile DBPs are also possible (Deng, 2021). Access to such options in Indonesia is very limited according to Daniel et al. (2023), and Ihsan and Derosya (2024). Thus, adsorption using locally available material, for example charcoal and/or biochar, can offer the better access option for most in developing nations.

Recent investigations into the efficiency of various HWTS methods – such as AC and membrane filtration, boiling, UV lamps, cold storage, or a combination of these – for DBP removal in drinking water have shown significant removal of trihalomethanes (THMs) and haloacetic acids (HAAs) using all these methods except storage. It varies according to the mechanism of purification and chemical characteristics of the target DBPs (Xiao et al., 2020).

It is important to note that pathogens must not be compromised as the means of controlling DBPs. Further research needs to be done on tradeoffs of chemical and microbiological risks in household water treatment, especially in Indonesia where exposure to both DBP and waterborne disease are plausible. This will also consider the peculiarities and challenges of Indonesia regarding diverse sources of water, prevailing types of pathogens, and various socioeconomic features that affect the way water treatment technologies would reach these households.

Evaluation of household chlorination

Household chlorination programs necessarily have to be very uniquely assessed for their effectiveness, since their success equates to safe drinking water and improvement in public health. Being a country with many diverse geographical conditions, socio-economic factors, and cultural practices, Indonesia requires a holistic approach in evaluation.

The microbial water quality at the household level will need to be monitored regularly in order to learn about the effectiveness of chlorination in reducing contamination. This is possible through testing for indicator organisms such as *E. coli* or total coliforms (Pachepsky et al., 2018). It is difficult to sustain consistent and appropriate monitoring in Indonesia, particularly in rural areas with limited access to facilities and trained personnel. Community-based monitoring and other approaches, including simple low-cost test kits that can surmount such challenges, could be quite innovative. Another such innovation is from Ramirez et al. (2023).

Free chlorine residual measurement in stored water is a means of ensuring that the chlorine levels remain adequate to prevent recontamination (Murray and Lantagne, 2014). However, FCR can dissipate quickly, especially in Indonesia's warm climate, where water is often stored in open containers exposed to sunlight (Saboe et al., 2021). Frequent measurement may be necessary, which can be challenging in household settings. Moreover, effectiveness of chlorination may be improved by promoting correct storages and raising awareness in users about the use and proper maintenance of FCRs.

Proper dosage and contact time of chlorination, proper storage: this is how user compliance could be measured. User compliance may also be affected by social and cultural norms of Indonesia. People have traditional ways and beliefs regarding the storing and treatment of water, which again is to be considered. It would be necessary to foster appropriate use and alleviate concerns through effective communication and community mobilization fitted within a particular cultural context.

This assessment of the impact of household chlorination on the incidence of waterborne diseases is very important in the community. However, due to other various factors influencing health improvement, such as sanitation and hygiene practices, it cannot be solely attributed to chlorination (Solomon et al., 2020). In Indonesia, diarrheal diseases are one of the biggest public health problems, and an integrated approach has to be brought in between chlorination, improvement in sanitation, and hygiene.

Sustainability in household chlorination programs depends on many factors in the long term, including product availability, chlorine affordability, local supply chains, and continued user support and education. According to Crider et al. (2018), with access to resources and markets sometimes varying greatly between and within regions in Indonesia, ensuring access to chlorine products and ongoing support for users was critical to program sustainability.

Strategies for effective implementation of household-based chlorination

In the scale-up of household chlorination programs, many factors are considered in an attempt to ensure wide acceptance and correct use for effective and sustainable results. The Indonesian context is culturally diverse with different socio-economic conditions, each with its own geographical challenges that any successful implementation must take into consideration. User acceptance and adherence need to be encouraged. Effective communication strategies must consider local beliefs and practices. For example, in Indonesia, where traditional water storage and handling practices may vary across different communities, messages should be tailored to address specific concerns and promote the benefits of chlorination in a culturally sensitive manner (Engel, 2021; Vel et al., 2022). Community engagement is also vital, involving local leaders and community members in program design and implementation. Participatory approaches can help in building trust and ownership, ensuring the program falls within the realm of community needs and preferences.

Meanwhile, improving access to adoption barriers plays a key role. Cost is typically the major barrier for households throughout Indonesia, especially in more rural areas; thus, access to chlorine products has been a challenge, and considering either subsidies or alternative ways of financing is critical (Ye and Dela, 2023). Furthermore, the accessibility of chlorine products is also important through access via local markets and different channels of distribution. For example, perceived taste and odor nuisance can be balanced with practical demonstrations and community education programs that show just how easy and convenient chlorination can be.

Selection of chlorine products is another step in careful choosing. Commercial chlorine-based products, like WaterGuard, are normally of good quality commercially; however, they usually sell with fixed-dose systems and thus require certain container sizes for this purpose (Mazhar et al., 2020; Mohamed et al., 2015). This is not constantly available in Indonesian households in the required doses (Irianti et al., 2016). These cases would, therefore, result in underdosage or a stoppage of disinfection altogether. This barrier can be overcome through the promotion of more flexible dosing methods, such as tablets and liquid chlorine, with easy-to-understand instructions and measuring aids.

In some Indonesian communities, concentrated NaOCl is purchased from a wholesaler, diluted, and then sold in smaller quantities. Although this may constitute a positive development toward greater access, unless the practice is carefully regulated and monitored, the potential for dosing and handling errors may pose some level of risk. This may better be accomplished through increased quality control and the training of vendors on appropriate dilution and handling techniques.

For many parts of Indonesia, locally produced chlorine solutions may be more available. However, they are always of inferior quality and stability when compared to commercial products. Capacities building and technology transfer supporting local production could raise the quality and consistency of such solutions in view of safety and efficacy assurance.

Other keys to successful implementation involve trying to bridge the gap between research interventions and reality. In Indonesia, consistent chlorination practices have proved to be a challenge, underlined by inconsistent use and under-dosing, especially when people use both untreated and treated water (Fagerli et al., 2017). Support and education for users become important to be continuously upheld, especially in the cases of chlorination techniques, doses, time of contact, and storage.

Lastly, the integration of chlorination with other WASH interventions would facilitate comprehensive measures for improving safety in relation to water and public health. According to Lantagne et al. (2011) chlorination needs to be done alongside improvements in hygiene and sanitation practices and, therefore, may be expected to add value in countries such as Indonesia, where diarrheal disease burden still remains very high, in an additive manner. Addressing these factors and appropriately tailoring the interventions to the specific needs and challenges in Indonesia would make household chlorination programs more effective in their provision of safe drinking water and improve public health outcomes.

Efficiency, compliance, and sustainability of household chlorination

Household chlorination can be a very strong tool in combating waterborne diseases, but access to safe drinking water remains a challenge in countries like Indonesia. However, the long-term success of household chlorination programs depends on a delicate balance of factors: efficiency of chlorination in eliminating pathogens, consistent user compliance with treatment protocols, and overall sustainability of these initiatives within diverse social and environmental contexts (Cheung, 2017).

The effectiveness of chlorination for ensuring safe drinking water is dependent on the type and concentration of chlorine applied, the contact time with water, the pH and temperature of the water, and the types of pathogens involved. All these variables must be put into great consideration to reach an optimum efficiency. For instance, although higher concentrations of chlorine and longer periods of contact generally increase pathogen inactivation, exceeding the safe limits may result in taste and odor problems that are undesirable and may discourage user acceptance (Bloodgood et al., 2022). Resistance among different pathogens to chlorine disinfection also varies. In addition, protozoa like Cryptosporidium, a common cause of diarrheal illness in Indonesia, are particularly resilient and may require higher dosage or increased contact times for complete inactivation to take place (Wijayanti, 2017). This again emphasizes that different approaches will be necessary to ensure the removal of all relevant pathogens in any particular context.

In Indonesia, raw water quality can greatly affect how well chlorination works. Sources throughout the archipelago range from pristine springs in mountainous regions to highly contaminated rivers in crowded cities. High turbidity and organic content, as might occur in surface sources commonly used in rural Indonesia, lowers the effectiveness of chlorine either by shielding pathogens or by consuming free chlorine. Consequently, the determination of water quality is a pre-requisite before the chlorination programs are undertaken, and pre-treatment processes such as filtration or sedimentation should be done where necessary. Efficiency may also be affected by the choice of chlorine product. Commonly used in Indonesia include sodium hypochlorite (NaOCl) and calcium hypochlorite ($Ca(ClO)_2$) (Zubir et al., 2020). NaOCl is widely used for household applications; it is easy to use and readily available. Still, its stability depends too much on storage conditions or even exposure to sunlight. On the other hand, $Ca(ClO)_2$ is pretty stable but requires much careful handling and may result in a residue in the water treated. The appropriate choice of chlorine product should consider many factors: cost, the accessibility of the products and user preferences, and also all the water quality conditions.

Even the best designed chlorination program will fail if users do not apply the treatment consistently and correctly. Chlorination of water at the point of use has been shown to reduce the risk of diarrhea in children (Ercumen et al., 2015; Solomon et al., 2020). However, past field studies show that adopting and consistently using chlorination has been a challenge. If chlorination is carried out regularly, but users do not consistently drink the treated water (e.g., consuming untreated water outside the home), compliance will remain low, so the health effects will also be low or non-existent (Murray et al., 2020). User compliance is crucial for ensuring that water remains safe throughout storage and consumption. Precious factors that might influence compliance may include knowledge and understanding about how chlorination is done, availability of resources and enabling support, cultural beliefs about handling water, and any perceived benefits or risks due to the treatment. Cultural practices and beliefs in dealing with water vary across communities in Indonesia, and consideration must be given to these perceived factors for effective promotion of consistent and proper chlorine application. For instance, the traditional methods of storing water, like earthenware jars or uncovered containers, have to be replaced to maintain the effectiveness and safety of chlorinated water (Manga et al., 2021).

The socio-economic status serves to either motivate compliance. Income constraint, limited literacy rate, and insufficient access to information becomes an obstacle toward adoption and maintaining chlorination (Crider et al., 2023; Locher et al., 2024). Considering income and educational equality, a strategic approach would have to include targeted interventions in order not to miss these vulnerable groups, and availing them an equal opportunity to enjoy safe water in Indonesia. Geographical settings also represent a factor that can favor or be used against it. Indonesia's vast archipelago poses logistical challenges in ensuring access to chlorine products and providing support to remote communities. Establishing efficient supply chains and strengthening local capacity for chlorine production and distribution are essential for promoting program sustainability (Murray et al., 2020).

There is also the issue of long-term sustainability. Long-term sustainability of household chlorination programs faces various challenges to be overcome, including ensuring reliable supplies of subsidized but high-quality chlorine products, mainly in the most remote areas of Indonesia, maintenance of users' motivation, ongoing support through education, integration of chlorination into larger WASH initiatives, that has its synergies, hence offering a contribution to sustainability as expressed by Briceño et al. (2017). For example, considering chlorination together with the promotion of hygiene practices, it would enhance sanitation facilities as a better way of reducing resultant burden from waterborne diseases, as Locher et al. (2024) have asserted.

Indonesia has carried out several efforts to scale up household water treatment through chlorination. The PAMSIMAS program was one of those community-based water supply and sanitation programs where chlorination was one of the key interventions to scale up access to safe drinking water in rural areas. While PAMSIMAS has achieved considerable success in increasing access to safe water, challenges remain in ensuring consistent chlorination practices and long-term sustainability (Bulo et al., 2024; Data.worldbank.org, 2019). Factors such as community ownership, local capacity building, and integration with other WASH interventions are crucial for the program's continued success. Other studies in Indonesia have explored the effectiveness of different chlorination methods and approaches to promoting user compliance.

Additional recommendations that may be considered to further improve efficiency, compliance, and sustainability of household chlorination programs in Indonesia include: community engagement in and ownership of the program should be strengthened; assure access to quality-assured chlorine products through efficient supply chains, including local production initiatives; ongoing support and education of users, including training on proper chlorination techniques, dosage, contact time, and safe storage practices; chlorination should be integrated into broader WASH interventions as a holistic approach to improving water safety and public health; and further research is needed to ascertain the effectiveness of various methods of chlorination, thus identifying factors influencing the outcomes of such programs in Indonesia. By learning from the successful and unsuccessful programs and adjustment of interventions to fit the needs and challenges in particular settings, Indonesia can better tap into the benefits contributed by household chlorination toward improvement in public health while ensuring access to quality drinking water for all citizens.

Barriers and drivers for adequate implementation

Household chlorination can bring about significant improvements in public health, especially in Indonesia, by reducing the burden of waterborne diseases. Realizing this potential will require a more complex understanding of both the barriers to and the drivers of successful implementation. Chlorination has indeed been one of the most effective methods of disinfecting drinking water; however, there are its own limitations. Chlorination is effective under only certain conditions, and inappropriate practices or discontinued use often leads to low efficiency in the field. Past research has addressed issues of water quality and the presence of FCR rather than actual chlorination practices in the field (Ihsan and Derosya, 2024). This has resulted in no clarity on whether reported failures are due to user-dependent factors-such as too short contact time, wrong dosage-or from factors independent of users, including high chlorine demand, poor product quality, or posttreatment recontamination. Further research will be needed to address these knowledge gaps with a view to informing interventions.

The main barriers to successful implementation include a lack of awareness and knowledge about the importance of water treatment and the benefits of chlorination. There are also misconceptions about chlorine safety and efficacy (Crider et al., 2018). It would also involve targeted education and awareness campaigns in Indonesia, due to the traditional practices and beliefs concerning water being different from one community to another, to address such knowledge gaps and promote acceptance of chlorination. This would entail clearing any myth or rumor concerning the toxicity of chlorine, especially in those areas where water is associated with some kind of healing power or spiritual significance.

The other most important barrier is accessibility and affordability. Inaccessibility to chlorine products because of remoteness, and the unaffordability of chlorine, may reduce adoption (Crider et al., 2023). Given the socio-economic disparities in Indonesia, access to chlorine products at an affordable cost must be equitably provided either by strengthening supply chains, subsidizing the cost of chlorine, or encouraging local production initiatives. It is worth mentioning that, whereas generally in a very inexpensive category, chlorine products will need to be replaced constantly and that need and frequent replacement requirement is considered an added cost to poor households, and may prevent adoption in the long term.

Even where chlorine is available and not prohibitively expensive, user compliance may be problematic. Poor or inconsistent use due to lack of knowledge, motivation, or perceived inconvenience will reduce effectiveness in chlorination programs. Promotion of user compliance in Indonesia, where cultural practices and beliefs in the handling of water may vary, promoting user compliance requires culturally sensitive approaches with ongoing support and education. This includes the lack of motivation among some people to do chlorination, even though they are aware of the advantages (Inungu et al., 2016). This can be addressed through long-term health benefits, simplification of the chlorination process, and building trust in testimonials and community involvement. Misconceptions of the correct procedures, including proper dosage and contact time, further render chlorination ineffective, thus discouraging its continued use. Clear and simple instructions, practical demonstrations, and ongoing support can considerably improve the level of understanding and compliance. This is most critical in Indonesia, where, with a variety of chlorine products available and different storage container sizes, the opportunity for incorrect dosing-meaning less effective chlorination-is increased.

Water quality is another critical factor for successful chlorination programs. High turbidity or organic content in water sources can reduce the efficacy of chlorine and may call for higher doses or additional pre-treatment steps (Léziart et al., 2019). In Indonesia, given that many communities rely on surface water sources that are prone to contamination, addressing the challenges of water quality is of prime importance to ensure that chlorination works effectively. Moreover, if treated water is not well stored, its recontamination can easily happen and cancel the chlorination effectiveness (Noh et al., 2016; Xiao et al., 2020). Safe storage and recommended container use are especially needed in Indonesia, as traditional ways of storing water are not always effective in helping to maintain its quality.

Other limiting factors include the acceptability of chlorinated water. At higher concentrations, the taste and odor of chlorine are unfamiliar or displeasing to some. That is very relevant in Indonesia because most people are unaccustomed to the taste of chlorinated water due to the fact that their application is not usual in public water supplies. This barrier might be addressed with optimization of chlorine dosages to minimize taste and odor problems (Crider et al., 2018), the promotion of alternative POU methods which have a less obvious sensory effect, or public education campaigns to make people familiar with the taste of chlorinated water and emphasize its safety (Ercumen et al., 2015; Ihsan et al., 2023, 2024; Johan et al., 2023).

On the other hand, some factors can be considered drivers for the successful implementation of household chlorination programs. This may include strong government commitment to supportive policies such as subsidy inclusion for chlorine products into national WASH programs or regulations regarding water quality monitoring that could help in the wide-scale adoption of services. Communities that are involved in the design and implementation process can take ownership of such a program and make it more sustainable. In Indonesia, with very strong community networks, leveraging the same for promoting chlorination and empowering communities to take charge of their water safety often works wonders. Clear and culturally appropriate communication strategies that emphasize benefits of chlorination and address concerns will promote user acceptance and compliance. In Indonesia, due to the existence of diverse languages and cultural practices, the communication messages need to be tailored to different audiences. Collaboration among government agencies, NGOs, private sector actors, and research institutions can strengthen these programs by making them more sustainable. Since Indonesia is the country where a quite good number of organizations work in the WASH sector, partnership can leverage resources and expertise in the better reach and impact of the chlorination program. Finally, regular monitoring of water quality, user compliance, and health outcomes can provide valuable feedback for program improvement and demonstrate the impact of chlorination. In Indonesia, with generally limited data on both waterborne diseases and chlorination practices, strengthening its monitoring and evaluation systems can provide valuable insights for program planning and decision-making.

CONCLUSIONS

Household chlorination can offer a promising solution to the lingering problem of waterborne diseases in Indonesia. It has been an important component in upgrading water quality at the point of use, especially when access to safe drinking water is limited. Success or failure of such programs is influenced by many interacting factors, including water quality, pathogen resistance, chlorine stability, disinfection by-product formation, user compliance, and socioeconomic and cultural influences.

The major issue identified is, in fact, high users' dependence for efficient disinfection. The technological approach, taking into consideration such water quality and organic matter content to avoid unwanted taste and odor and DBPs, requires much accuracy in applying the right dose. This emphasizes correct dosing strategy that might be implemented according to the water source type and points forward to the importance of end-user education and support for implementing chlorine correctly.

Additionally, some of the key challenges for the implementation of household chlorination programs in Indonesia included: variation in the quality of the source water, the presence of chlorine-resistant pathogens, maintenance of the stability of chlorine in a tropical climate such as that of Indonesia, health concerns arising from the formation of disinfection by-products, and assurance of user compliance and long-term program sustainability. These call for a multidimensional approach that incorporates the peculiar environmental, social, and economic contexts of Indonesia.

Although it is the best, cheapest, easiest, and most accessible household water treatment intervention, low compliance with chlorination is still a major challenge facing Indonesia, especially within the rural areas. Poor compliance among end-users usually emanates due to lack of motivation; this sets in the need to explore user behavior change coupled with water quality awareness to minimize risks of consuming untreated water. This emphasizes that access to chlorine is not enough but rather ownership and the sense of responsibility by the community for their own water safety.

Analysis of the current chlorination practices at households reveals that though chlorine is well recognized as a classic disinfection method, its application is not effective in practice. This therefore, calls for addressing implementation barriers, consistent and correct use of chlorine at household level with appropriate communication strategies, continued support and education, linking of chlorination with WASH initiatives.

Still, there are a few opposing circumstances to better the efficacy of HCC at scale in Indonesia. Indeed, community involvement and ownership create opportunities for appropriate and sustained adoption of chlorination. Improve access to quality-assured chlorine products through reliable supply chains and local production initiatives-availability assured even at deeper levels. Long-term support will be required to advance appropriate technologies, help address concerns, and sustain motivation. It was learned that chlorination acts synergistically with other WASH improvements, such as sanitation and hygiene practices, to reduce the burden of waterborne diseases. Finally, further research is needed to evaluate different chlorination methods and identify factors influencing program success in the Indonesian context.

In conclusion, while chlorination has shown to be effective for household water disinfection, it is essential to acknowledge its limitations and the potential of alternative methods. The choice of the most suitable method should consider various factors, including cost, ease of use, effectiveness against different pathogens, and local context. In Indonesia, where water quality and access to resources vary significantly, a combination of methods or a multi-barrier approach may be most effective in ensuring safe drinking water. Further research is needed to address the challenges of user compliance and program sustainability, and to optimize chlorination practices for the Indonesian context.

Declaration of competing interest

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

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