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DRINKING WATER PROBLEMS IN RURAL AREAS: REVIEW OF POINT-OF-USE METHODS TO IMPROVE WATER QUALITY AND PUBLIC HEALTH

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ABSTRACT

Waterborne pathogens from poor sanitation are the main cause of drinking water problems facing humanity in the 21st century, leading to infections and diarrhea. This results in over half a million deaths annually, with most of them occurring in developing countries such as Indonesia. Due to the lack of access to centralized water treatment facilities, point-of-use (POU) systems have been suggested as an important solution for water treatment in developing communities. These systems are user-friendly, low-cost, low-maintenance, and do not depend on the power grid. Importantly, they treat and reduce the number of pathogens in the water supply, and many POU systems have been implemented and used by communities on a household scale. However, the POU system has limitations that hinder its implementation in Indonesia. To examine and evaluate the technology implemented in POU systems, this review focuses on systems that can serve households or communities. The advantages, disadvantages, and limitations of technology that have existed in the last decade are explained. By taking the case of Indonesia, it is hoped that this review can provide an evaluation and illustration of its application in similar developing countries. Another affordable technological solution suggested that could benefit people relying on unsafe water sources.

Keywords: Drinking water treatment, Developing countries, Rural communities, Point-of-use, Indonesia

ABBREVIATION

BSF	bio-sand filtration
CDC	Centers for Disease Control and Prevention
DBP	disinfection byproduct
HWT	household water treatment
HWTS	household water treatment and storage
LDH	Layered double hydroxide
POU	point-of-use
RO	Reverse osmosis
SODIS	solar disinfection
UNICEF	United Nations Children’s Fund
WaSH	water, sanitation, and hygiene
WHO	World Health Organization

INTRODUCTION

The issue of access to safe drinking water is of global significance and brings to the fore the social and economic disparities that exist. Access to clean drinking water is a fundamental right that should be enjoyed by all individuals, regardless of their location or socio-economic status. However, it is unfortunate that over 30% of people in underdeveloped regions still do not have access to improved drinking water (UNICEF, 2015). According to the World Health Organization/ WHO (2022), at least 2 billion people worldwide, mostly in developing countries, consume water contaminated with feces, leading to an estimated 485,000 deaths annually due to diarrheal diseases. To address this issue, the WHO/UNICEF Joint Monitoring Program (JMP) recommends a range of better water sources (WHO and UNICEF, 2021), including pipe networks, tube wells, protected dug wells, springs, and rainwater reservoirs. In the past few years, considerable progress has been made in the field of water treatment and distribution, enabling people to gain access to better-quality drinking water (Patel et al., 2023; Umrigar et al., 2023). These advancements have resulted in the creation of new and improved methods for purifying water and making it fit for human consumption. As a result, individuals and communities around the world now have access to safer and cleaner sources of drinking water, which has had a significant positive impact on public health and well-being.

In well-developed countries and bustling urban centers, a centralized water treatment system is in charge of overseeing the water supply. This system employs a variety of methods to eradicate harmful microorganisms from the water, after which the treated water is distributed to homes through a vast network of pipelines. However, rural areas and developing countries face challenges when it comes to implementing centralized water treatment and distribution systems due to the high initial expenses and low population density. Developing a complete water treatment plant package takes a long time and requires other social factors to be considered. The global issue related to drinking water contamination is becoming increasingly urgent and needs to be addressed as soon as possible.

In Indonesia, a developing country, the majority of water sources are considered to be at risk for waterborne diseases. Out of the 20 thousand drinking water sources in Indonesia, 70 percent are contaminated with fecal waste or E. Coli bacteria, according to UNICEF Indonesia in 2022 (UNICEF Indonesia, 2022). Escherichia coli, Enterococcus, Cryptosporidium, and rotavirus are the main causes of most cases of diarrhea in developing countries (Plutzer and Karanis, 2016; WHO, 2017; Efstratiou et al., 2017; Ugboko et al., 2020). Therefore, WHO drinking water guidelines indicate that drinking water and its distribution system should not have detectable fecal coliforms (WHO, 2006).

It is estimated that nearly half of Indonesia's population experiences waterborne diseases every year, with nearly ten thousand children under five dying from diarrhea alone (Arivia and Ratnadi, 2021). In Indonesia, numerous rural communities lack access to piped water supply and instead resort to alternative sources such as open wells, hand pumps, rivers, ponds, and small-scale irrigation reservoirs for drinking water. Regrettably, these sources are susceptible to contamination by pathogens, as noted by Indriatmoko and Rahardjo (2015). Even tap water supplied to cities and villages through centralized water treatment plants may contain detectable levels of pathogens (Nastiti et al., 2013; Sari et al., 2019; Jern, 2022; Ikhsan et al., 2022).

As education increases, more people in urban areas are becoming aware of water problems and are taking measures to purify household water before consumption. However, in remote areas, there is always a risk of contaminated or unsafe water, which has led to the rise of bottled water suppliers and an increase in plastic waste pollution. Additionally, expensive bottled water can sometimes be unreliable. Natural disasters like earthquakes and tsunamis can also contaminate local water supplies, leaving people with no choice but to consume unsafe water (Patil et al., 2020). Portable, affordable, user-friendly, and easy-to-carry water treatment systems play a critical role in ensuring safe drinking water. These systems can efficiently disinfect contaminated water on-site, thereby reducing the risk of waterborne diseases. Implementing on-site water treatment and storage systems is a viable option in developing countries, especially in rural areas. Point-of-use (POU) technology is an on-site water treatment solution that eliminates pathogens from source water before consumption. In the past decade, several POU processing technologies have emerged and been applied in different parts of the world. This paper aims to review and evaluate technologies that have been developed in the last two decades and are used in POU treatment systems in Indonesian communities. The goal is to identify effective technologies that can eliminate pathogens and reduce diarrhea cases.

CURRENT APPROACHES FOR POU WATER TREATMENT

When it comes to choosing a water treatment method for a household or community, there are several factors that need to be taken into consideration. When assessing the feasibility of installing water, sanitation, and hygiene (WaSH) facilities, several factors come into play. The existing water and sanitation conditions in the area, including water quality, have a significant impact on the success of the project. Cultural acceptance and appropriateness are also important considerations, as well as accessibility and the availability of technology. Moreover, consistent and long-term usage of the facilities is crucial for their effectiveness and sustainability. Finally, other local conditions, such as environmental factors and community attitudes, should be taken into account to ensure that the WaSH facilities are appropriate for the specific context. To make water safe from dangerous germs, there are various methods that can be used, such as boiling, chlorination, filtration, and solar disinfection (CDC, 2022).

Boiling

Boiling water using fuel is an age-old method of disinfection that is highly effective against all types of pathogenic microbes (WHO, 2015). It is an established method to make it safer to drink. Therefore, people confidently trust this remedy and rely on it for their drinking water. However, this process requires a considerable amount of fuel, which could cost up to $10.56 per person annually (Clasen et al., 2007). In many rural areas, people rely on wood as the main source of fuel for boiling water. Boiling water, contributes to indoor air pollution, which can lead to respiratory issues in households (Raju et al., 2020). Boiling water at temperatures higher than 55°C can help kill most waterborne microorganisms like pathogenic bacteria, viruses, worms, and protozoa. A study conducted in rural areas of Indonesia found that when the boiling temperature was raised to 70°C, coliforms were reduced by 70% (Sodha et al., 2011). Despite its effectiveness, boiling water poses significant health risks due to indoor air pollution, smoke, greenhouse gas emissions, and reduced forest area (Walsh and Mellor, 2020; Sarita et al., 2023). Furthermore, boiled water is prone to recontamination because it is often cooled in open containers (Gärtner et al., 2021; Imtiyaz et al., 2021).

Chlorination

Chlorination is a common method used to disinfect raw water. However, there are some issues that require attention. To ensure effective germ-killing, it is recommended to apply chlorine in pipes or mixing tanks instead of storage tanks. This is because chlorine can react with organic materials and settle at the bottom of storage tanks. For at least 15 minutes, the free chlorine concentration should be maintained at a minimum of 0.4 to 0.5 mg/L (Buse et al., 2019; Zhang et al., 2021). Chlorine tablets, chlorine gas, or hypochlorite solution can be used as a source of chlorine, and the dosage levels vary according to the amount of chlorine required in the water. Filtration can help to lower the levels of natural organic matter or total organic carbon in water, which can subsequently reduce the need for chlorine treatment. However, for water with higher turbidity, more chlorine may be required to maintain safe levels of disinfection (Wilhelm et al., 2018). One limitation of chlorination is that it may not be effective in eliminating certain protozoa such as Cryptosporidium and Giardia (Khan and Witola, 2023). Additionally, the taste and odor of chlorinated water may not be desirable to some people, which could restrict the use of chlorine treatment products (Crider et al., 2018). Strategies to mitigate these issues include adjusting the pH of water before chlorination, using activated carbon filters to remove byproducts and improve taste and odor, and community education to address perceptions and increase acceptance (Srivastav et al., 2020).

Filtration

Filtration is a water treatment process that removes impurities. This process works through size exclusion. However, because filter pores are larger than microorganisms, filtration does not remove all pathogens. Ceramic filters, on the other hand. Ceramic filters are effective against protozoa, bacteria, and viruses, making them the best option for removing pathogens, making them more effective in removing pathogens. A well-designed filtration system will produce clean drinking water, which gives users confidence in the filters as they tend to purify water effectively. Ceramic filters can also be used to cool water through evaporation (Pichel et al., 2019). However, these filters are fragile and expensive to maintain, with an estimated cost of $3.03 per person annually (Clasen et al., 2007). Stone filters are similar but generally less fine, making them more suitable for larger particulates; sand filters are effective for turbidity reduction and some pathogen removal, particularly when used in multi-barrier systems combining coagulation and disinfection steps (Clark et al., 2012). The most common filtration technology used at the POU is membrane filtration (besides bio-sand filtration/BSF). Membrane filtration typically requires an external driving force to achieve the desired flow rate, which depends on the membrane pore size, surface area, and inlet water quality. A higher pressure is required to filter water across a smaller membrane area with a smaller pore size. It is important to note that during the filtration process, a layer of foulant will build up on the filter layer after an extended period of use. In sand filtration, recoverable flux can be restored through backwashing. On the other hand, in membrane systems, backwashing only removes reversible fouling, while chemical cleaning is necessary to eliminate biofouling and scale (Du et al., 2020).

SODIS

This disinfection method is a simple and cost-effective method of water treatment that uses sunlight to purify water. The process works by utilizing the germicidal effect of UV light and the synergistic effect of increased water temperature (Clasen et al., 2007). SODIS is particularly effective in places where sunlight is strong, such as Indonesia, African countries, and other countries with almost year-round sunshine. The water is stored in bottles or containers and is then dried in the sun. During this process, the temperature of the water in the container can reach approximately 60 degrees Celsius. This is enough to make many microorganisms inactive due to the sunlight and heat produced. UVA radiation from the sun is lethal to bacteria, while UVB radiation is lethal to bacteria, viruses, and protozoa (García-Gil et al., 2020). This treatment is very cheap, as it only requires a transparent container made of glass or plastic, which costs an estimated $0.63 annually per person (Clasen et al., 2007). It is also worth noting that there are no adverse effects on the taste of the water. However, it is recommended that treated water be consumed within 24 hours of exposure as bacteria can grow again in the dark when the water is stored and cooled (García-Gil et al., 2020).

RESULTS AND DISCUSSIONS

Filtration serves as a method for physically eliminating microorganisms from water, and it is widely applied in Indonesia and other developing nations to secure potable water. Water traverses a porous structure composed of diverse base materials or a membrane, capturing suspended particles, including microorganisms, contingent on the filter's pore size (Betancourt and Rose, 2004). Common household filters, such as ceramic, stone, or sand filters, effectively employ a combination of pore filtering, adsorption onto filter granules, sedimentation in media pores, and coagulation during pore traversal to eliminate suspended particles (Betancourt and Rose, 2004). Regular cleaning of these filters is crucial to prevent contamination of the water by dirty filters. Slow or fast sand filters, while intricate, prove more adept at pathogen removal, making them preferable for water supplies in smaller communities (WHO, 2017).

In membrane filtration, water undergoes filtration through a thin film that selectively removes pathogens based on their size. Microbes exceeding the membrane pore size are thereby eliminated. Reverse osmosis (RO), a pressure-driven process employed in areas with limited water resources, is effective for desalination and drinking water production. However, the removal of microorganisms through RO is discouraged due to potential membrane damage caused by persistent biofilms formed by bacteria on the membrane surface (Dvorak et al., 2014; Stoica et al., 2018). This poses a critical challenge to the operational efficiency and cost-effectiveness of membrane systems, necessitating chemical cleaning and membrane replacement. Additionally, ROs demand high energy input due to substantial electricity consumption during feed stream pressurization (Ghaffour et al., 2013; Zotalis et al., 2014; Patel et al., 2020; Mahmoud et al., 2023). Cloth filtration, utilized at the household level in developing countries, is another technique for water treatment. However, it is not deemed suitable for drinking water treatment (Francis et al., 2016).

Chlorination stands out as a cost-effective, readily applicable method, widely endorsed for household water treatment in rural settings by NGOs, local organizations, and governments, owing to its numerous advantages. However, challenges at the household level include selecting the most pertinent household water treatment (HWT) method, ensuring optimal disinfection efficiency, accurately determining the appropriate chlorination dose, and addressing taste, odor, and disinfection byproduct (DBP) concerns, particularly in water sources containing specific organic materials. Despite chlorine's efficacy, cost-effectiveness, and simplicity, low compliance poses a significant hurdle in rural and developing regions. This challenge often stems from insufficient end-user motivation, emphasizing the necessity for research into user behavior changes and awareness concerning water quality risks. Social aspects, frequently overlooked, play a crucial role, as households may reject disinfected water due to aversions of chlorine taste and smell (Crider et al., 2018). Even in public water supplies, issues like inadequate dosage hinder chlorine use, exemplified in Indonesia (Susanto et al., 2022). Addressing these challenges requires comprehensive research merging social, scientific, and engineering perspectives, delving into real domestic scenarios and technology limitations, and proposing alternative approaches. This approach aims to instigate long-term behavioral changes, elevate compliance rates, and mitigate user attrition from chlorination programs.

For any public health intervention addressing water contamination in rural areas, careful investigations are recommended to mitigate taste concerns and disinfection byproducts in households. This entails water quality assessments, pathogen screening, potential multi-barrier strategies, and the design of user-friendly devices like inline chlorinators. In rural communities, microbiological water contamination, linked to inadequate treatment and distribution, poses a significant risk. Challenges in rural areas, particularly in Indonesia, including intermittent water supplies, leaks, poor water quality, and inadequate maintenance, impede effective chlorination. Barriers to proper chlorination application result in low success rates, attributed to lacking risk assessments and limitations in biological contamination characterization, sampling, and detection. Inadequate knowledge about correct chlorination application, insufficient dosage leading to inefficiency, incorrect practices, and discontinuation contribute to challenges. Monitoring and evaluating water sources in rural communities pose substantial obstacles, highlighting the need for user-level awareness empowerment through behavioral change, encompassing technical training on water quality, hygiene habits, and purification. Achieving effective and sustainable chlorination requires building capacity and capabilities at community and local government levels, ensuring continuous support for sustainability. Scrutiny of chlorination practices in Indonesia reveals a gap between its widespread recognition and its effective household application. Moreover, a lack of long-term monitoring and compliance measures necessitates further research to address the efficacy of household-level chlorination implementation, particularly focusing on compliance. This review underscores the challenges inherent in household-based water treatment interventions and emphasizes the imperative for capacity building during community and household interventions, necessitating an understanding of how chlorination is practiced in terms of dosage, contact time, water qualities, and the potential need for a multi-barrier approach.

The SODIS of water, a method deemed suitable for Indonesia, presents certain drawbacks in developing countries compared to alternative household water treatment and storage approaches such as chlorination or filtration (Clasen et al., 2007). One notable disadvantage stems from the absence of dedicated commercial products for water disinfection under SODIS, resulting in a lack of substantial funding from large manufacturing companies for promotional campaigns. The vials utilized in SODIS are typically designed for diverse purposes, leading to manufacturers' reluctance to endorse this method. In developing countries, there is often skepticism among the populace when introduced to SODIS, as they may anticipate more technologically advanced solutions for water pollution issues. While SODIS is not a universal remedy for safe drinking water access, other household water treatment and storage (HWTS) interventions can be equally, if not more, effective at a higher cost. Despite its limitations, SODIS stands as a cost-effective household intervention against waterborne diseases, making it more economical than other alternatives (Clasen et al., 2007).

Over the last decade, SODIS adoption has been primarily driven by economic benefits, including reduced fuel costs for water boiling and diminished morbidity and disease-related expenses. SODIS serves as a gateway HWTS intervention, enabling households to transition to more reliable yet pricier water treatment methods suitable for higher altitudes. Laboratory studies confirm the efficacy of SODIS against nearly all species of waterborne pathogenic microbes (García-Gil et al., 2020). Clinical trials conducted in developing countries indicate that when correctly implemented and consistently used, SODIS can significantly reduce childhood dysentery and diarrhea rates by up to 45% (McGuigan et al., 2012). Currently, more than 4.5 million people in over 50 developing countries utilize SODIS daily. Future challenges revolve around refining microbicide processes and devising effective strategies for enhancing HWTS. The following table, Table 1, presents a comparison of all the POU options.

Table 1. A comparison of the most commonly used point-of-use (POU) water treatment methods

Method	Taste	Advantages	Disadvantages
Chlorination	Tastes of chlorine	Effective against a variety of pathogens, providing a broad spectrum of disinfection. Chlorine residual can provide continued protection against recontamination after initial treatment.	It is not effective for a few protozoa like cryptosporidium. Needs constant supply. Safety risk if it is not properly stored.
SODIS	Good	Remove most of the bacteria and protozoa Relies on sunlight, making it a low-cost method that does not require additional chemicals or energy. The method is simple, involving filling transparent containers with water and exposing them to sunlight.	It is not effective if sunlight does not stay longer and is less strong. No protection from recontamination.
Boiling	Smokey/flat	Remove most of the bacteria and protozoa,	Environmentally unstable and can contribute to greenhouse gas emission

Method	Taste	Advantages	Disadvantages
		Simple process and Inexpensive.	if wood/coal is used. Can reduce forests.
			Can damage respiratory system due to poor air quality. Can be recontaminated if stored water has no recontamination protection.
Filtration		Effectively remove suspended particles, sediment, and larger microorganisms from water.	Can clog over time, reducing their effectiveness and requiring frequent maintenance or replacement.
		Can improve the taste and odor of water by removing certain organic and inorganic substances.	Some filters may not effectively remove viruses or certain types of bacteria, depending on their pore size and design.

FUTURE CHALLENGES

Adsorption is a cost-effective method for sterilizing water by removing bacteria and viruses from it (Sellaoui et al., 2021). However, this method has not been widely used in POU (point of use) practices. Most adsorbents are available only in powder form, which makes it difficult to use them for batch water treatment because they must be separated from treated water through methods such as filtration. One possible solution is to shape the powder adsorbent into a physical form, which would make it easier to move in and out of the water. Several research studies have attempted to implement this approach (Sadia et al., 2022; Johan et al., 2023, Ihsan et al., 2024). However, the study does not provide a comprehensive overview of the synthesis process and material characteristics.

Layered double hydroxide (LDH) can adsorb most bacteria and viruses in water (You et al., 200; Forano et al., 2018), although this fact was not covered in the review by Sellaoui et al. (2021). LDH is harmless to humans and is used in pharmaceuticals (Forano et al., 2018). It is also effective in adsorbing bacteria such as *Escherichia coli* (*E. coli.*: ATCC 15597 and 13706) and *Bacillus subtilis* (Jin et al., 2007; Liu et al., 2013), along with bacteriophage viruses like MS2 and øX174 (You et al., 2003; Park et al., 2012) from water. This adsorption ability is due to the positive charge of LDH, which attracts the negatively charged surfaces of most bacteria and viruses through electrostatic forces (Liu et al., 2013; Forano et al., 2018). However, due to the powdery nature of LDH, its utilization in batch or column methods presents inherent difficulties, thus limiting the practical application of LDH in POU water treatment methods (Dou et al., 2022).

Recent investigations have shown that it is possible to synthesize LDH onto aluminum plates, creating an immobilized LDH (Bouali et al., 2020; Fukugaichi et al., 2022). Utilizing immobilized LDH facilitates the efficient adsorption and removal of pathogens from batch water, such as that stored in household water jugs. However, it is important to sterilize the water immediately before use to avoid the risk of pathogen contamination during transportation or after bringing it home.

An immobilized LDH foil suitable for batch water disinfection was prepared by immersing aluminum foil in seawater containing sodium hydroxide, resulting in the formation of Mg-Al-type LDH on the foil's surface (Johan et al., 2023; Ihsan et al., 2023). Although the LDH foil method has proven effective, its widespread adoption may be hindered by certain drawbacks. To address these challenges, an alternative approach involving the simple preparation of an alkaline solution is proposed. This approach significantly simplifies the preparation of the solution for immersing aluminum foil, potentially making it more user-friendly and accessible, especially in resource-limited settings.

CONCLUSION

Our comprehensive review of Point-of-Use (POU) water treatment systems highlights their critical role in addressing the urgent water quality issues faced by rural communities in Indonesia and similar developing regions. By comparing different POU technologies—such as boiling, chlorination, filtration, and solar disinfection (SODIS)—we have identified both the strengths and limitations of each method in context-specific applications. These technologies have demonstrated significant potential to improve drinking water quality and public health outcomes by effectively removing pathogens and reducing contamination. However, each technology has its own set of advantages, disadvantages, limitations, and implementation challenges when it comes to serving underserved communities

Moving forward, it is imperative to foster community engagement and education to enhance the adoption and sustained use of these POU systems. Additionally, further research into integrating multiple treatment methods could offer robust solutions tailored to the unique environmental and socio-economic conditions of each community. Our findings underscore the necessity of continuous innovation and local capacity building to ensure that safe drinking water remains accessible to all, thereby upholding basic human health and dignity in underserved populations.

By focusing on practical, scalable solutions and community-based approaches, we can make significant strides toward overcoming the barriers to clean water access. This endeavor not only supports public health improvements but also contributes to broader socio-economic development goals, affirming the indispensable role of safe water in fostering sustainable, healthy communities. In addition, the potential use of adsorbents, such as Layered Double Hydroxide (LDH), as a new POU tool is a promising development that could significantly improve water quality and health outcomes for underserved communities.

Declaration of competing interest

The authors 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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