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Mitigating the Drinking Water Crisis in Developing Regions – A Comprehensive Evaluation of Disinfection Technologies

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ABSTRACT

Securing clean drinking water in developing countries is imperative for human survival, yet persistent challenges exist in cost implementation and technical operations. This paper aims to assess disinfection methods, with a focus on the efficacy of chlorination and ozonation in neutralizing bacteria. By thoroughly examining both conventional and advanced disinfection techniques, the paper offers a comprehensive perspective on potential solutions. The analysis scrutinizes key parameters, particularly the efficiency in neutralizing bacteria, revealing chlorination and ozonation as standout methods. Furthermore, considerations of cost-effectiveness underscore the viability of diverse options, including solar disinfection, solar pasteurization, alternative pasteurization methods, chlorine dioxide, and filtration. In essence, this paper serves as an essential resource for those navigating the complexities of water quality and accessibility, particularly in regions where the need is most acute.

Keywords: drinking water, disinfection techniques, developing regions, cost effectivities.

INTRODUCTION

The current era is marked by significant challenges regarding the diminishing accessibility of water resources, which is one of the foremost environmental concerns across numerous countries. Projections have proven that approximately two-thirds of nations worldwide are poised to tackle water stress by 2025. The insufficiency in addressing the impact of distribution networks on water quality, primarily due to the scarcity of comprehensive data quantifying the extent of this public health issue, often results in overly optimistic rather than realistic assessments of distribution network conditions (Budihardjo et al., 2022; Syafrudin et al., 2024). In 1994, when the coverage data were compiled, the population of developing nations was approximately 4.4 billion. Subsequently, in 1995, the total population of developing countries was estimated to be 4.53 billion, with 37% residing in urban areas and 63% in rural regions based on the data of the United Nation (Cotruvo et al., 2019).

In 2018, the Safe Drinking Water Foundation (SDWF) made a significant disclosure, indicating that approximately 80% of health-related problems in developing countries are attributed to the consumption of unsafe drinking water (Unicef 2018). Numerous studies have examined the lack of drinking water in developing countries. For instance, one highlighted study underscored the critical necessity of comprehensive measures to enhance access to safe drinking water in these areas. This imperative goes beyond improving public health and extends to safeguarding the well-being of the most vulnerable segments of the population (Abedin et al., 2019). The persistent prevalence of this situation is detrimental to several aspects, including national stability, public health and welfare, and the depletion of human potential and resources. Despite efforts by many developing countries to implement regulations and provide access to safe water, this problem persists. There is concrete evidence that certain countries are struggling to effectively address this issue, as evidenced by the guidelines for implementing optimal monitoring practices in resource-constrained settings (Puspita et al., 2023). The scarcity of financial, human, and technological resources hampers a nation's capacity to monitor its water supply effectively. Monitoring practices have been assessed in several developing countries, including India and Peru (Crocker and Bartram 2014). This approach serves as a practical and forward-thinking strategy to address crucial aspects of public health and human well-being while simultaneously bolstering the overall development prospects in developing countries (Cotruvo et al., 2019). However, a research gap exists regarding the absence of drinking water, particularly in the in-depth analysis of the financial implications and operational costs associated with implementing solutions in developing countries.

Therefore, this study distinguishes between the alternative methods for disinfecting drinking water, considering both technical operations and cost-effectiveness.

THE PROBLEM OF DRINKING WATER ACCESS

Water quality and health

A report by the World Health Organization (2002) outlined sets of risk factors contributing to health problems, one of which is linked to the environment. These factors play a pivotal role in shaping public health outcomes and are critical considerations in health policies and interventions. Table 1 presents data on the environmental risk factors for health.

Existing problem in developing regions

The research will focalize on the unique characteristics inherent to Developing Countries, placing specific emphasis on a rigorous data analysis pertaining to the prevailing status of potable water implementation, the allotment of financial resources for the establishment of drinking water infrastructure, and the mean Gross Domestic Product (GDP) generated within the intricate framework of nations in the process of development. Economic downturns and instability resulting from global crises have the propensity to exacerbate poverty levels in developing nations. Instances of such crises encompass political upheaval, international fluctuations in oil prices, the specter of terrorist threats, and the worldwide financial crisis, all of which have contributed to an escalation in socioeconomic uncertainties (Tran et al., 2021; Budihardjo et al., 2023).

In the assessment of government performance concerning the management of drinking water resources in developing countries, a multifaceted approach is employed, encompassing six essential dimensions of governance: these include voice and accountability, which measures the government's responsiveness to the needs and opinions of its citizens; political stability and the absence of violence, examining the security and stability of the political landscape; government effectiveness, which assesses the government's capability in efficiently executing its functions and delivering essential services; regulatory quality, focusing on the effectiveness and robustness of regulatory policies and frameworks governing water resource management; the rule of law, which gauges the extent to which legal principles are upheld to ensure fairness and justice; and control of corruption, which measures the government's efforts to combat corruption and maintain transparency in water resource management (Bayu et al., 2020). The findings of this assessment are presented in a structured tabular format for comprehensive analysis in Table 2. Figure 1 displays remittances to developing countries using data from the World Bank database.

The data and static above makes a significant contribution by quantifying access inequality within developing countries, a dimension frequently overlooked in prior reports that predominantly rely on aggregate statistics and national population access figures. Specific focus centers on the disparities to get the facility of drinking water. This approach illuminates a dimension that has been somewhat underrepresented in existing literature, which predominantly concentrates on spatial, social, and urban-rural disparities. Due

Table 1. Environmental risk factors to health

Risk factor	Theoretical minimum	Measured adverse outcomes of exposure
Water, sanitation, and hygiene risks	Exposure	Diarrhea and other illnesses related to the risk factor
Urban air pollution	Prevention of diarrheal disease transmission through improved water, sanitation, and hygiene practices	Cardiovascular mortality.
Indoor smoke from solid fuels	7.5 µg/m for PM25	Deaths related to respiratory issues, lung cancer, and mortality resulting from acute respiratory infections in children
Lead exposure	No solid fuel use	Respiratory infections in children, chronic obstructive pulmonary disease, lung cancer, cardiovascular disease, and mild mental retardation

Note: source – WHO (2002).

Table 2. Discovered factors in water governance that affect access to basic water and sanitation services, connected to indicators in the GLAAS and WGI databases

Water governance factors	Water Government Indicator	
	Water	Sanitation
Executing the government's designated funding strategy.	The presence and extent of implementation of a government-defined financing plan/budget for the WASH sector, published and agreed upon, for both urban and rural areas.	Presence and extent of implementation of a government-defined financing plan/budget for the WASH sector, published, and agreed upon, in both urban and rural areas.
Clarity and reliability of financial reporting	Publicly available and easily accessible expenditure reports that enable the comparison of committed funds to actual expenditures in both urban and rural areas.	Reports on expenditures are openly accessible and easily available, facilitating the comparison of committed funds to actual expenditures in both urban and rural areas.
Reliability in managing foreign aid and external funds.	Utilization of external funds as a percentage of official donor capital commitments, calculated as a three-year average, for both urban and rural areas.	Utilization of external funds as a percentage of official donor capital commitments, calculated as a three-year average, for both urban and rural areas.
Utilization of local funds.	Utilization of domestic funds as a percentage of domestic commitments, calculated as a three-year average, for both urban and rural areas.	Utilization of domestic funds as a percentage of domestic commitments, calculated as a three-year average, for both urban and rural areas.
Financial strategy aimed at supporting vulnerable populations.	Specific measures in the financing plan to direct resources to vulnerable populations, encompassing various elements such as PP, project implementation[a] (PP. PK, PD, WM, PI, PR, IP)	Specific measures in the financing plan to target resources to vulnerable populations[a] (PP. PR. PD, WM, PI, PH, IP)1. Policies and plans have specific measures to reach vulnerable groups (PP. PR, PD. WM, PL, PH, IP)
Strategies and initiatives to support vulnerable populations.	1. Policies and plans include the measures the vulnerable groups[a] (PP, PR. PD, WM, PI, PR, IP) 2. Monitoring progress among vulnerable groups.	1. Policies and plans have specific measures to reach vulnerable groups[a] (PP. PR, PD. WM, PL, PH, IP) 2. Monitoring progress among vulnerable groups.
Inclusive policy and regulation.	Level of involvement or engagement, distinguishing between urban and rural areas.	Level of involvement or engagement, distinguishing between urban and rural areas.
Effectiveness of government and quality of regulations.	1. Government effectiveness[b] 2. Regulatory quality[b]	

Note: The code stands for this terms: [a]PP – poor populations, PR – populations living in remote areas, PD – people with disabilities, WM – women, PI – populations living in slums or informal settlers, PB – populations with high burden of disease, IP – indigenous populations. [b]Indicators from WGI.

to the characterization, the core problem is the regulation and systematic system on providing the best solution for drinking water which related to social and economic. Thus, in accordance with the suggested solution, a two-fold assessment will be conducted to identify the most suitable approach for addressing the challenges of drinking water provision in developing countries. The first assessment will focus on evaluating the environmental impact, which is closely linked to the

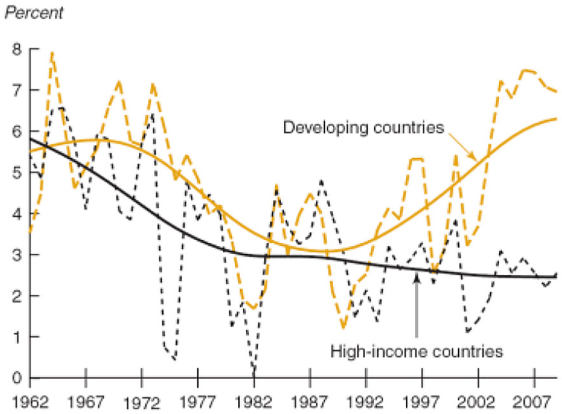

Figure 1. The growth of GDP in both developed and developing nations from 1962 to 2007. Source – World Bank, Global Development Finance 2008

underlying social concerns. The second assessment will examine the cost-effective implementation to address the economic aspects of this issue.

COMPARISON ON DISINFECTION TECHNOLOGIES

Disinfection is the final step in treating drinking water, and is designed to eliminate harmful microorganisms that cause waterborne diseases. This crucial process can be performed using physical or chemical methods to effectively reduce the number of microorganisms in water, but the technologies is different with wastewater treatment (Priyambada et al., 2023). Thus, it plays a crucial role in protecting public health and preventing the spread of waterborne illnesses (Pichel et al., 2019). The survey was conducted in Canada and served as a benchmark for assessing the efficacy of disinfection methods in different population groups.

Conventional technology

GAC scenario

This treatment method is commonly utilized in drinking water treatment plants, particularly for eliminating trace organics present at concentrations ranging from nanograms per liter (ng/L) to micrograms per liter (μg/L). Over time, the adsorption capacity of Granular Activated Carbon (GAC) decreases the natural organic matter (NOM) and trace organics. Ultimately, the GAC becomes saturated, diminishing its ability to effectively remove these contaminants (Yuan et al., 2022). GAC filters are widely used to remove organic carbon in drinking water treatment. GAC is preferred over PAC because of its cost-effectiveness, as PAC has experienced a significant cost increase (Clark et al., 2020).

One hypothesis explaining the continued effectiveness of the GAC performance is the

Table 3. Classifications according to population size and the main disinfection methods used in 2004 and 2006

Population groups		The primary disinfection method					
		None	Free chlorine	Free chlorine & chloramines	Chlorine dioxide & chlorine-based	UV & chlorine-based	Ozone & chlorine based
2004	[0, 1,000)	0	1	0	0	0	0
	[1,000, 2,000)	4	23	1	1	1	0
	[2,000, 5,000)	3	22	1	0	1	0
	[5.000, 50,000)	5	53	2	2	11	3
	[50,000, 500,000)	4	9	7	1	2	5
	[500,000 & more)	1	3	0	0	1	0
	% of all	10.18	66.47	6.59	2.40	9.58	4.79
2006	[0, 1,000)	0	11	0	0	1	0
	[1,000, 2,000)	2	10	0	2	2	0
	[2,000, 5,000)	3	13	1	0	3.	05
	[5.000, 50.000)	6	35	3	0	13	5
	[50,000, 500,000)	0	8	5	0	4	4
	[500,000 & more)	0	2	0	0	1	1
	% of all	8.15	58.52%	6.67%	1.48%	17.78%	7.41%

potential desorption of previously adsorbed contaminants, followed by their degradation by microorganisms that thrive on the carbon surface. This process contributes to the partial regeneration of in-service GAC. An alternative hypothesis posits that biodegradation takes on a significant role as an alternative mechanism responsible for the removal of geosmin in GAC, referred to as "biofiltration." This transformation of GAC from solely an adsorption process to GAC biofiltration may have the potential to prolong its service life, thereby avoiding the need for costly replacements (Yuan et al., 2022).

The comprehensive cost estimation for common granular activated carbon (GAC) implementation, particularly concerning capital expenditure, integrates the utilization of an infrared reactivator with the overall operational infrastructure being meticulously assessed, as detailed in Table 4. This table provides a thorough breakdown of costs along with detailed explanations of each component, offering a comprehensive overview of the financial aspects associated with GAC implementation.

Ozone scenario

Ozone is primarily generated by the reaction of oxygen molecules with oxygen atoms, a process facilitated by gas discharge, photochemical excitation, and electrochemical reactions. Although silent discharge is commonly used in ozone generators because of its effectiveness, it has limitations. The ozone produced by this method is susceptible to consumption via thermal decomposition and side reactions, limiting its practical application (Wei et al., 2017). To improve ozone yield efficiency, combining silent discharge with surface discharge in hybrid methods is more effective.

Ozone is produced by the interaction of a substantial amount of energy with oxygen molecules (O_2), causing their separation into individual atoms (O). Subsequently, these atoms react with other oxygen molecules to form ozone molecules (O_3). There are several viable alternatives for cost reduction in ozone generation equipment.

1. Lowering the generated ozone consumption per unit (grO_3/kWh) makes the process more energy efficient.
2. Decreasing the dimensions of the cells and/or utilizing high-voltage transformers contributes to the overall cost savings by optimizing the physical components.
3. Developing electric sources that are both more efficient and cost-effective can potentially lead to substantial long-term economic benefits for the ozone generation process.

Table 4. Estimated cost for GAC method

Cost, $/year	
Item	GAC/year
Capital	355,639
Makeup GAC	502,651
Power-fuel	150,278
Materials	83,647

Ozonation is a costly technology in terms of both initial capital investment and ongoing operational expenses. The ozone treatment process requires significant energy input, on-site generation capabilities, skilled maintenance, and incorporation of post-treatment procedures to address the considerable levels of assimilable and biodegradable organic carbon generated during oxidation. Moreover, ozone interacts with natural organic substances and bromide ions (Br-), leading to the generation of various byproducts such as bromate, aldehydes, ketones, and quinones. Significantly, the occurrence of trihalomethanes (THMs) and haloacetic acids (HAAs) is absent, and even when chlorine is utilized as a secondary disinfectant, their formation can be minimized (Pichel et al., 2019).

Chlorination

Chlorination is the prevailing method for disinfecting drinking water and treating wastewater to mitigate the growth of pathogenic microorganisms. However, when chlorine interacts with natural organic substances in water, harmful byproducts such as trihalomethanes, haloacetic acids, and haloacetonitriles are generated. The obligation to govern harmful disinfection has steadily become more stringent, leading to the heightened scrutiny of alternative chemical disinfection approaches (Ofori 2018). High-purity chlorine was procured and meticulously processed. To create the stock solutions, pure chlorine gas was carefully passed through distilled water that had been purged with oxygen using nitrogen gas (Pichel et al., 2019). Freshly prepared stock solutions were subjected to a precise calibration process via amperometric titration, as outlined in recognized "Standard Methods." This study assessed the impact of turbidity on drinking water quality in six watersheds and found that distribution line turbidity levels averaging 2.4 NTU. Chlorination significantly reduced the coliform counts by an average of 63-fold. High-turbidity water (13 NTU) retained 20% of the coliforms after disinfection, whereas low-turbidity water (1.5 NTU) rendered the coliforms undetectable. Disinfection efficiency correlated negatively with turbidity ($r = -0.777$), highlighting the effectiveness of chlorine, especially in low-turbidity water (<1 NTU, $pH < 8.0$), and ensuring sustained disinfection in distribution and storage systems. (WHO 2011). Despite the proven efficacy of chlorination as a water disinfection technique, it is important to note that conventional automated chlorine dosing plants utilizing chlorine gas require a skilled workforce comprising highly trained operators and engineers.

Chloramination

In the early 1970s, during the initial identification of disinfection byproducts (DBPs) in chlorinated drinking water, a substantial body of research was dedicated to understanding the mechanisms responsible for DBP formation and developing effective strategies for their control and mitigation (Wei et al., 2017). Organic chloramines can be generated when dissolved organic nitrogen (DON) includes functional groups, such as amino acids, amides, and amines, within dissolved organic carbon (Pichel et al., 2019). In aqueous systems, this process involves a reaction between free chlorine and organic chloramines. Organic chloramines were synthesized by introducing sodium hypochlorite into specific precursor solutions, where the molar ratio of sodium hypochlorite to the precursors (including amino acids and amines) was maintained at 0.2. This molar ratio has been demonstrated to effectively reduce undesired side reactions while facilitating the preferential formation of monochloramine. An identical ratio was employed for the chlorination of amides to ensure a consistent approach (Li et al., 2011). Chloramination requires comparable dosing equipment and trained operators, yet results in fewer taste and odor concerns and does not lead to the formation of trihalomethanes (THMs).

Chlorine dioxide

Chlorine dioxide (ClO_2) is a practical alternative to the traditional chlorination methods for water disinfection. It demonstrated significant efficacy in eradicating bacteria, viruses, and protozoans. An advantage of chlorine is its ability to prevent the formation of carcinogenic disinfection by-products (DBPs). However, it's worth noting that the by-products it does produce, namely chlorite (ClO_2^-) and chlorate (ClO_3^-), are subject to regulatory standards in drinking water. Chlorine dioxide also serves as an excellent oxidizing agent for managing the presence of phenolic compounds that contribute to taste and odor issues as well as for the removal of iron and manganese from water. Chlorine dioxide was initially synthesized by Davy in 1814 through the reaction of sulfuric acid (H_2SO_4) with potassium chlorate ($KClO_3$). Subsequent scientific explorations revealed several similarities in the properties of chlorine. It is a relatively small, volatile, yet highly energetic gaseous molecule that exists as a free-radical monomer, even when dissolved in an aqueous solution (Masschelein 2021). Chlorine dioxide (ClO_2) has certain drawbacks, including a relatively low effectiveness against Cryptosporidium oocysts, which are resilient microscopic organisms. Additionally, ClO_2 can cause taste and odor issues in treated water, restricting its applicability as a secondary disinfectant in certain contexts.

UV lamps

Over the last decade, ultraviolet light-emitting diodes (UV-LEDs) have become increasingly popular as a viable technology for water disinfection (Song et al., 2018). UV-LEDs offer similar advantages for water disinfection as traditional mercury-based UV lamps but also overcome some of the drawbacks associated with UV lamps. Unlike conventional UV lamps, UV LEDs are mercury-free, more compact, robust, less prone to damage from frequent cycling, have longer lifespans, and achieve full power output more rapidly. These benefits, along with an almost instant startup and the ability to adjust wavelengths, contribute to significant flexibility in the design of UV LED water disinfection systems (Bowker et al., 2011).

In contrast to numerous disinfectant chemicals, UV treatment does not introduce taste or odor to water and carries no risk of overdosage or the formation of harmful byproducts (Gadgil 1998). Traditional UV reactors, which usually use mercury lamps, are currently being validated using a method called biodosimetry. In biodosimetry, the sensitivity of a surrogate test microorganism to UV exposure is measured at different doses using well-calibrated inactivation kinetics.

For UV reactors, the dose-response curve is typically generated by testing the microorganisms in the test water under collimated beam conditions. The inactivation of the biodosimeter, along with the calibration curve, was then used to calculate the reduction equivalent dose (RED) in millijoules per square centimeter (mJ/cm^2). To ensure accurate and consistent results, it is crucial that the challenge organisms used in biodosimetry originate from the same stock of microorganisms and are cultivated in the same manner.

The primary concern associated with UV disinfection is the substantial energy requirement of lamps over their entire lifecycle. This encompasses the energy consumption during manufacturing and operation (requiring a continuous electricity supply), as well as the energy needed for maintenance and disposal. UV lamps typically need to be replaced every 6–12 months, leading to frequent replacements and additional energy expenditure involved in manufacturing and transporting new lamps.

Additionally, the disposal of used lamps presents a waste management challenge because of the presence of hazardous mercury. Addressing this environmental impact requires recycling lamps to recover reusable materials and control Hg emissions. As UV lamps require annual replacement, recycling significantly influences the overall energy consumption of UV disinfection systems. Another constraint is the relatively low efficiency of mercury-based UV lamps, which typically ranges from 15% to 40%. Considering the electrical conversion efficiency of lamps (typically approximately 35%), the final efficiency of UV disinfection systems falls within the range of 5–15%. These factors underscore the need for energy-efficient and environmentally friendly disinfection technologies (Pichel et al., 2019).

Pasteurisation

Boiling water for disinfection, known as pasteurization, is effective, but requires a significant amount of fuel. High fuel consumption renders this method unsustainable and expensive (Bowker et al., 2011).

Gathering wood for boiling water imposes a substantial burden on millions of citizens in the developing world. Additionally, it is economically impractical and environmentally unsustainable for the routine disinfection of water. The physical labor involved in wood collection, the associated time commitment, and the environmental toll of deforestation make it an unviable and unsustainable option for the daily purification of water in many developing regions.

Filtration

Drinking water processing typically involves several key stages of filtration methods, including encompass coagulation-flocculation, sedimentation, and gravity filtration through granular media. The main objective of these methods is to aggregate suspended solids and colloids, leading to the formation of settleable flocs that can be easily removed from sedimentation basins (Hardyanti et al., 2023). Gravity filtration through specialized granular media such as sand or activated carbon is commonly employed as the final step in refining the quality of drinking water (Bowker et al., 2011).

The Thessaloniki drinking water treatment plant in Northern Greece explored new methods and compared them to traditional ones. They tested dual-media and direct filtration without an intermediate sedimentation step against a standard single-sand filtration bed with sedimentation. This study assessed the effectiveness of single- and double-layer filter beds in the usual drinking water treatment process involving coagulation, flocculation, sedimentation, and bed filtration.

Point-of-use (POU) water treatment methods have become recognized as practical solutions for addressing water challenges in developing nations. Recent reviews of water, sanitation, and hygiene interventions have highlighted the potential to improve household drinking water quality in POU, leading to a decrease in diarrheal diseases.

The primary aim of point-of-use (POU) household water treatment (HWT) and safe water storage technology is to empower individuals who lack access to safe water sources. These technologies allow people to improve water quality by treating and safely storing water in their homes. Various POU technologies offer policymakers, implementers, and users a range of options. The choice of specific POU technologies depends on the unique circumstances and target populations, providing a flexible toolkit to enhance water quality and reduce health risks from contaminated drinking water. Consequently, these methods have gained popularity and become essential for addressing water-related challenges in many developing countries. It is crucial for individuals to remain motivated and committed to incorporating POU technologies into their daily routines beyond their initial educational programs. For POU technology to be truly effective, it must be sustainable, seamlessly fit into the daily lives of all household members, and consistently used for drinking, food preparation, handwashing, and other essential purposes. The key features of sustainable POU technology are as follows.

1. Consistent Production: the technology should reliably produce sufficient microbiologically safe water to meet daily household requirements.
2. Versatility: effective treatment of a variety of water sources and quality levels, including turbid and organically rich water.
3. User friendly: the process should be efficient and require minimal user time to treat water without significantly increasing household labor.
4. Affordability: the technology should have low cost and be relatively insensitive to income fluctuations, ensuring that households can afford and maintain it.
5. Accessibility: there should be a reliable and affordable supply chain for replacement units or parts that consumers can easily obtain.
6. Long-term Use: the technology should maintain high usage levels, even after intensive surveillance and educational efforts.

The desalination process demands substantial energy input, primarily owing to the significant electricity consumption during feed flow pressurization. Producing one cubic meter of fresh water from brackish water typically requires 0.5 to 2.5 kWh of energy. For seawater desalination, the energy requirement increases to 3–10 kWh per cubic meter. The substantial energy expenditure of desalination processes, especially for seawater, highlights the need for energy-efficient technologies and sustainable practices (Ghaffour et al., 2013).

Emerging technology

In addition to the established conventional disinfection methods employed in drinking water systems, advanced technologies are also available for the purification of drinking water.

Solar pasteurisation

Solar thermal pasteurization is a cost-effective and straightforward method for producing safe drinking water. This technique harnesses solar energy to heat water to a sufficiently high temperature for a specified duration, thereby effectively inactivating or destroying pathogenic microorganisms. (Ray et al., 2014). This approach is particularly prevalent in developing nations where access to electricity or firewood is limited.

Solar disinfection

Solar disinfection (SODIS) is a cost-effective point-of-use (POU) technology that involves the simple process of exposing water-filled polyethylene terephthalate bottles to sunlight. However, it is important to recognize that only a specific part of the solar spectrum, ultraviolet A (UVA), plays a role in the disinfection of SODIS (McGuigan et al., 2012). Furthermore, achieving 3-log (99.9%) inactivation of certain viruses under typical weather conditions may require an extended duration of over 30 h of sunlight exposure. Recognizing these limitations and aiming to utilize solar energy more efficiently, researchers have explored advanced point-of-use (POU) disinfection technologies (Fisher et al., 2008).

Despite this progress, there are limited data on the comparative efficacy of various solar point-of-use (POU) technologies owing to challenges in accurate comparisons, including unrealistic solar irradiation levels in research studies (Jeon et al., 2022). It is worth emphasizing that diverse POU technologies require specific pretreatment methods for the removal of interfering constituents present in water as well as for pathogens that are not easily inactivated by the chosen technology. Moreover, disparate studies often employ distinct target pathogens for investigation, with a bias toward those already proven to be susceptible to the selected disinfection approach. In contrast, the limitations of a given technology in terms of its ineffectiveness in inactivating other pathogens are frequently not explicitly acknowledged (Ray et al., 2011).

Photocatalysis

Photocatalysis is now considered a viable option alongside the current methods for treating drinking water (Jeon et al., 2022). The amount of H_2O_2 in photocatalysis is low, requiring high concentrations for effective water treatment. These by-products may be more easily biodegradable. However, the use of photocatalysis for industrial water treatment is challenging. In slurry TiO_2 systems, an additional step is required to recover the catalyst particles and prevent losses of new

Table 5. Result comparison in each method of disinfection

Method	Advantages	Disadvantages
Chlorination	- Highly efficient at neutralizing bacteria and viruses. - Provides enduring safeguards against potential re-contamination. - Basic equipment and instrumentation are all that's necessary for calcium and sodium hypochlorite applications.	- Formation of disinfection byproducts (DBPs) - Limited effectiveness against Cryptosporidium and Giardia cysts - Unpleasant taste and odor issues - Reduced efficacy in water with high turbidity and organic content - Sensitivity to pH levels - Chlorine gas poses significant hazards and is highly corrosive - Necessitates skilled operators
Chloramination	- Exhibits lower disinfection byproducts (DBPs) compared to chlorine. - Offers continuous protection against potential re-contamination. - Effectively combats the formation of biofilms within the distribution system.	- Requires on-site production. - Exhibits lower disinfection capability compared to other methods.
Chloramination	- Presents fewer taste and odor concerns.	- Requires trained operators - Relying on the availability of chemicals is essential.
Chlorine dioxide	- Reduced reliance on pH compared to chlorine. - Exhibits prolonged residual effectiveness.	- On-site manufacturing is necessary. - Comes at a higher cost than chlorine.
Ozonation	- Demonstrates effectiveness against bacteria, viruses, and protozoa, including Giardia and Cryptosporidium. - Not dependent on the availability of chemicals.	- On-site production is essential. - Lacks the ability to maintain a residual effect. - Costs associated with it are considerably higher in comparison to other chemical disinfectants.
UV lamps	- Demonstrates effectiveness against viruses, spores, and cysts. - There are no taste or odor issues. - It does not produce harmful byproducts. - Independent of the availability of chemicals.	- The system has low energy efficiency. - The lamps need replacement every 6 to 12 months. - The lamps contain toxic mercury. - Disposed lamps pose challenges for waste management.
Pasteurisation	- Simple to operate - Not reliant on the availability of chemicals.	- Demands a significant amount of fuel. - Poses challenges in terms of economic and environmental sustainability.
Filtration	- Decreases water cloudiness and microorganism levels. - Not reliant on the availability of chemicals. - In the case of reverse osmosis (RO), it produces water of high quality.	- The removal of pathogens relies on the filter's pore size. - Regular maintenance is necessary to clean the filters. - In the case of reverse osmosis (RO), it involves high energy consumption, elevated expenses, and the addition of chemicals for membrane cleaning. - Reverse osmosis is not recommended for eliminating microorganisms.
Solar pasteurisation	- Easy to operate and cost-effective. - Not reliant on electricity. - Does not produce harmful byproducts. - Independent of the availability of chemicals.	- Relies on weather conditions. - Involves a relatively lengthy water purification process. - Does not leave a lasting residual effect.
Solar disinfection	- Affordable and straightforward to operate. - No ongoing expenses for users once they acquire PET bottles. - Not reliant on electricity. - Does not generate harmful byproducts. - Independent of the availability of chemicals.	- Relies on weather conditions. - Takes a relatively extended time to purify water. - Requires pre-treatment when dealing with highly turbid water. - Lacks the ability to maintain a lasting residual effect.
Photocatalysis	- Demonstrates potent bactericidal activity.	- Relies on climatic conditions. - Requires access to chemicals.
Electrochemical disinfection	- Direct electrolyser: Not reliant on access to chemicals.	- Necessitates a continuous energy supply. - Involves considerations of electrode lifetime and chemical dependent

pollutants. The operational costs vary based on the spectrum of catalyst activation, with higher UV ranges corresponding to higher costs.

Electrochemical disinfection

Electrochemical disinfection deactivates microorganisms in water by applying an electric current through electrodes. This process, using at least one anode and one cathode, initiates oxidation and reduction reactions, ensuring effective water disinfection (De Wet 2018). Electrochlorination reduces trihalomethanes (THMs) by over 50% compared to chlorination alone but faces electrode lifespan variations. RuO2-coated Ti electrodes last three months, while uncoated Ti electrodes can last up to eight years (Ray et al., 2011). Based on the technology, related to comparison in disinfection technologies, here is the comparison as the conclusion of each method presented in Table 5 (Pichel et al., 2019).

CONCLUSION

This study highlights chlorination and ozonation as effective water disinfection methods. However, their cost-effectiveness prompts the consideration of diverse alternatives. Solar disinfection, solar pasteurization, alternative pasteurization methods, chlorine dioxide treatment, and filtration are viable options. To address the drinking water crisis in developing regions, a comprehensive strategy combining established and innovative techniques is crucial for factoring in cultural acceptance, regional challenges, and feasibility.

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