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Evaluation of Household Water Treatment Technologies for Cholera Eradication in Sub-Saharan Africa: Epidemiological and Economic Perspectives

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Abstract: Cholera has been a global pandemic in past centuries, and its persistent emergence and spread pose a significant public health challenge globally. Despite efforts to contain the disease, recurrent cholera outbreaks in sub-Saharan Africa remain a major health threat. This has attracted substantial research interest, raising questions about the effectiveness of prevention and control methods of cholera spread in sub-Saharan Africa. Addressing this health challenge by adopting a sustainable, convenient, and cost-effective intervention will improve the health, well-being, and productivity of vulnerable populations in sub-Saharan Africa. Household-level solutions, which are characterized by relatively low-cost and independence from potentially insufficient public water supply infrastructure were examined to determine their effectiveness in reducing the incidence of cholera if widely adopted across the continent. We perform a mixed-methods retrospective analysis on the Cholera epidemic data obtained from 2010 to 2016 in sub-Saharan Africa. Using an empirical epidemiological model, we estimate the performance efficacy of a suite of household water treatment (HWT) technologies. We also develop economic estimations to perform benefit–cost analyses to determine the cost effectiveness, convenience of use and durability of these products. We find that—if universally adopted—the HWT technologies evaluated here offer comparable and effective microbiological potential for eradicating cholera disease in sub-Saharan Africa but are potentially not affordable for low-income households that reside in cholera hotspots. As such, household subsidies are necessary in lowering barriers to economic access to these products. This finding provides substantial insights on the efficacy and affordability of these household water treatment technologies—insights which can inform stakeholder decisions on the applicability of this intervention in eradicating cholera.

Keywords: water contamination; water quality; cholera; Sub-Saharan Africa; household water treatment

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1. Introduction

Cholera is a highly infectious gastrointestinal disease characterized by excessive watery diarrhea and rapid severe dehydration, putting infected individuals at high risk of body fluid loss and death. Cholera is transmitted through either a fecal-oral pathway which occurs when people consume food or water that has been contaminated with fecal matter containing the Vibrio cholerae bacterium, or the direct person-person pathway, which involves contact with surfaces contaminated by the fecal matter of an infected person. This first pathway (i.e., contaminated water) is the main vehicle for the transmission of cholera, accounting for 80–90% of global cases [1]. One recent study analyzed data from 1426 cholera outbreaks in 69 countries and found that contaminated water was responsible for 82% of outbreaks, while contaminated food accounted for 18% of outbreaks [2]. Another Africa-focused literature review on cholera outbreaks found that waterborne transmission accounted for 90% of cases in endemic regions, while foodborne transmission was responsible for 10% of cases [3]. Over the past two centuries, six distinct cholera pandemics have occurred globally across all continents, with the ongoing seventh pandemic persistently impacting sub-Saharan Africa [4]. This current outbreak is leaving behind a trail of compromised health conditions and economic hardship as a result of population productive time loss, cost of treatment, and national health emergency responses to multiple outbreaks. In 2020, Nigeria the most populous country in sub-Saharan Africa reported an upsurge in cholera cases in October 2020, which transitioned into an epidemic in 2021. According to the Nigeria Centre for Disease Control Surveillance data [5], overall, 93,598 cholera cases and 3298 deaths (CFR: 3.5%) were reported across 33 of 37 states in Nigeria within the study period [6]. In 2021, another significant cholera outbreak occurred in Cameroon, resulting in 27,245 suspected cases and 622 deaths [7]. Most recently, Malawi witnessed a sporadic cholera outbreak that claimed 1210 lives between March 2022 and February 2023 [8]. Thus, it is clear that cholera continues to substantially impact the populations of multiple African nations.

Despite the decreasing trend in the case fatality rate (CFR) of cholera in most developed countries, the global rate remains nearly constant at 2% due to increasing CFRs of cholera in sub-Saharan Africa [9]. Previous cholera outbreaks in Africa have been associated with a high CFR, ranging from 7.6% to as high as 50% [10]. Approximately 1.3 billion people are at risk of cholera in endemic countries with an estimated 2.86 million cholera cases and 95,000 deaths annually [4]. The World Health Organization (WHO), which disseminates yearly statistical records of reported cases and deaths from cholera, estimates that only 5–10% of the cases occurring annually are officially reported [1]. This inconsistent reporting is attributable to multiple factors including limited capacity of epidemiological surveillance systems and laboratories, as well as social, political, and economic disincentives for reporting in endemic countries [4]. This plausibly suggests that there may be many undocumented incidences of cholera infection and outbreaks in sub-Saharan Africa. The region therefore requires urgent research attention to address this widespread public health challenge, which recent efforts are attempting to address (e.g., Global Task Force on Cholera Control [11]). Much of the research on cholera to date has focused on epidemiology and public health, pathogenesis and immunology, clinical management, vaccines, and immunization. However, little is known about the performance effectiveness and economic accessibility of household-level interventions in reducing the incidence. Insubstantial information exists on the geographic information science of cholera and how sustainable long and short-term interventions can consequently eliminate the incidence of cholera while accounting for geographic context. A recent meta-analysis found that household water treatment (HWT) interventions, such as chlorination and filtration, reduced the risk of cholera by 47% [12]. Another study found that an intervention combining improved water storage and chlorination significantly reduced the incidence of cholera in rural Kenya [13]. Another systematic review and meta-analysis found that point-of-use water treatment interventions, such as chlorination, filtration, and solar disinfection, were effective in reducing the risk of cholera by 47% [14]. These research works have proposed the effectiveness of specific household interventions. To eradicate cholera as a public health threat in sub-Saharan Africa, it is imperative that clean, reliable, and affordable drinking water options are provided, particularly for high-risk communities. Because of their relatively low-cost, effectiveness, and independence from (potentially insufficient) public infrastructure, household-level solutions are often promoted and adopted in high-risk communities. Household water treatment and safe storage can potentially play a pivotal and immediate role in improving the quality of drinking water and preventing water-borne diseases. Further, being a ‘point of use’ intervention, these treatment technologies can significantly reduce the risks of recontamination since they are implemented at the point of consumption, which ensures that water is treated immediately before use. In contrast, large-scale water supply infrastructure, such as centralized water treatment plants and piped water distribution systems, can be susceptible to contamination during distribution, storage, and handling if mismanaged or inadequately maintained [15]. Given the potential promise of these household-level solutions, it is important to perform an integrated economic and epidemiological analysis to quantify the potential household benefits and costs of utilizing such technologies.

To do this, we first perform a comprehensive classification of household water treatment technologies based on performance, durability, minimal environmental impact, affordability, convenience of use, and acceptability. We then categorize each product based on its microbiological performance and functional mechanism (i.e., membrane ultrafiltration, solar disinfection, flocculation-disinfection-filtration, flocculation-disinfection, and UV-disinfection). We then use a beta-Poisson model and log10 reduction estimates to quantify the concentration of infectious dose that has caused a case of cholera before and after treatment. Specifically, we perform a reverse dose-response calculation to estimate the magnitude of incidence reduction in high-risk regions across sub-Saharan Africa. We follow this epidemiological assessment by performing benefit–cost analysis to compare the total cost of procurement (for each treatment technology) and the average direct cost of cholera treatment for an individual. Finally, we quantify the total cost for all households to adopt the evaluated household treatment techniques and compare with the overall cost of implementing centralized safe water supply infrastructures across sub-Saharan Africa. In doing so, the study is not just limited to evaluating the extent to which the increased adoption of different household water filtration technologies can reduce cholera incidence in sub-Saharan Africa. It also assesses affordability of these different technologies to evaluate the potential effect that household subsidies may have in lowering barriers to economic access of these treatment systems. Understanding the efficacy and affordability of these household technologies can provide important first insights towards more effective interventions aimed at cholera prevention.

2. Methodology

We adopted a descriptive systems approach—considering health, economic, social, and environmental perspectives—and performed quantitative analyses using empirical epidemiological calculations and economic estimations. Secondary data were obtained from Lessler et al. [16] as well as reports from inter-governmental agencies including the World Health Organization (WHO), the centers for Diseases Control and Prevention (CDC), the United Nations (UN), the World Bank (WB), and the United Nations Children's Fund (UNICEF). The main source of information on household water treatment (HWT) technologies was Refs. [17,18].

2.1. Study Area

Sub-Saharan Africa is comprised of 48 countries with a population of approximately 1.3 billion people—roughly 16% of the world's population. It remains one of the most challenging public health contexts in the world with high disease burdens, limited access to quality health care, and significant disparities in health outcomes. Despite significant progress in recent years, the region continues to face a suite of pervasive life-threatening health challenges including cholera epidemics.

2.2. Epidemiological Analysis

We used the Quantitative Microbial Risk Assessment Model (QMRA) for our analysis [19]. The model involves several different stages: Hazards Identification; Dose-response Assessment; Exposure Assessment; Risk Characterization; and Risk management. We focused on the Dose-response assessment and assumed that during the cholera epidemic (2010–2016), the significant transmission pathway of infection was through drinking water sources, and hypothetically in the absence of household water treatment technologies evaluated in this study, while other environmental and epidemiological factors that could possibly influence the rate of infection remain constant.

Dose-response assessment is a critical step in epidemiological studies that examines the relationship between the amount of exposure to a particular substance, agent, or stressor and the potential health risk. In the context of this research, the number of pathogens responsible for causing an infection of cholera were measured as dose with the unit CFU/mL (colony forming unit per milliliter). We used the Beta-Poisson model which has been used in past epidemiological studies to determine the dynamics of cholera outbreaks and to inform control measures [20] (see Equation (1)). We then solved for the dose (D) to derive Equation (2). In our study, the efficacy of household water treatment technologies was measured on a logarithmic reduction scale (log10). The term "log reduction" may be used to measure the effectiveness of various processes, such as disinfection, sterilization, or other treatments that are intended to reduce or eliminate the presence of harmful microorganisms. For example, if a volume of contaminated water that is treated attains a 1 log reduction in the number of bacteria, it means that the number of bacteria has been reduced by a factor of 10 (i.e., by 90%, or 10 times fewer) while the dose capable of causing an infection was measured in colony forming unit per milliliter (CFU/mL). The mathematical equations below show relationship between dose in log10 and CFU/mL:

Beta-Poisson Model:

$$P(r) = 1 - \left(1 + D\frac{2^{\frac{1}{\propto}} - 1}{N50}\right)^{-\propto} \quad (1)$$

Derivative from the Beta-Poisson Model:

$$D = \frac{(1-P)^{-1/\propto} - 1}{\frac{\left(2^{\frac{1}{\propto}} - 1\right)}{N50}} \quad (2)$$

Log Reduction formulae:

$$L = \log 10\left(\frac{A}{B}\right) \qquad L = \log A - \log B \quad (3)$$

where P is the prevalence of cholera occurrence in a population, D is dose (CFU/mL), *N50* is the dose at which 50% of a population is expected to be affected (CFU/mL), α is a unitless empirically determined disease-specific parameter A is the number of viable microorganisms before treatment (CFU/mL), and B is the number of viable microorganisms after treatment (CFU/mL). In these equations, A is equal to D.

2.3. Economic Evaluation and Analysis

We determined the cost and rate of affordability of household water treatment technologies by evaluating the parameters, median household income of the population, and the total cost of procuring a technology. Because of the strong association between poverty and areas at high risk of cholera outbreak [21], we assumed that the average daily income of individuals that live in these cholera-prone areas is USD 2.15 per capita per day based on the recent World Bank report on poverty [22]. The value was then multiplied by 240 days, the estimated average working days per annum in Africa, and the average working household size of different sub-Saharan African countries [23] to determine the estimated household income per annum. The rate of affordability for each HWT technology was calculated as the ratio of the total cost of a HWT technology and household income per annum.

The motivation of our analysis is also to determine the cost-effectiveness of various HWT technologies. For comparison, we obtained data on the direct cost of treating a clinically confirmed cholera case [24]. The direct cost of treatment was estimated by considering the following expenses: (cost of medicine; cost of consultant/hospitalization; cost of cholera test; health care cost borne by the cholera patient; and cost of productive time lost—where we assume that a severe case of cholera involves five days of hospitalization).

Finally, combining the information on the cost of each HWT technology and the number of individuals living in high-risk areas, we created a hypothetical scenario to compare the total cost to provide a HWT technology to all high-risk households within each country against the estimated cost of financing the construction of public water supply infrastructure [25].

3. Results

We find that all household water treatment technologies evaluated in this study achieved and exceeded the required geometric average removal for bacteria pathogens as standardized by the United States Environmental Protection Agency (10^6 CFU/mL pathogen reduction). Putting into perspective the functional mechanism, cost, convenience, durability, storage, lifespan and life span and efficacy, we classified the household water treatment technologies (Table 1).

Table 1. Classification of HWT technologies. Information is provided on the functional mechanism, total estimated cost, storage and capacity, durability, and convenience.

HWT Products	Functional Mechanism	Total Cost (USD) Maximum Cost per Year	Efficacy (CFU/mL)	Storage and Capacity	Durability	Convenience of Use
LifeStraw	Microorganisms are physically removed through ultrafiltration from water as it is forced through hollow fiber membranes of pore size 0.1 µm–1 µm under gravitational pressure. Filter flow rate is 12 L/h.	Family 1.0: 147 Family 2.0: 489.3	7.3	Family 1.0: NO (can hang on wall) Family 2.0: YES (tabletop) 5.5 L.	Filter and tap to be replaced after 2–3 months. Products have a lifespan of 3–5 years	Needs user training and a reliable supply chain. Daily backwash and pre-filter cleaning recommended. Not energy-deficient.
AquaPak	Contaminated water heats at >65 °C using sunlight to eliminates all types of microorganisms, bacteria, viruses, and protozoa. It has colored wax that melts at 65 °C, indicating that water is safe for consumption.	23	7.3	YES (can hold 5 L of water).	The AquaPak can be reused daily and has a lifespan of 3 years.	Simple to use and no maintenance required. Minimal likelihood of recontamination when held in disinfecting container. Relatively long time to treat water and variability depending on sun intensity.
Solarbag	Solar powered -solar-activated nanotechnology. Suitable for highly turbid water. It uses Pur-Blue Dye Indicator for the first time to test the duration required throughout the treatment process. Photocatalysis breaks down blue dye in water at the same rate as contaminants.	65.5	6.0	YES (can hold 10 L of water).	Puralytics Solarbag lasts for 7 years.	Simple to use. No maintenance required. Minimal likelihood of recontamination when held in disinfecting container. Relatively long time to treat water and variability depending on sun intensity.
JAMEBI	Solar Powered (UV + Heat) technology. Heats water to 75 °C using sunlight, in the heat exchanger's outer pipe. Then, the solar thermal panel pasteurizes at ~80 °C for 4 min. Pasteurized water is cooled in the heat exchanger's inner pipe before release.	216.7	6.4	NO (maximum daily output is 250 L/day) = 1,000,000 L of water throughout its lifespan.	Reusable for 20 years in daily use.	Solar-powered. No electricity required. Easy to use based on design principle. Weekly visual maintenance checks required for leaks. Annual maintenance to clean heat exchanger. Minimal need for spare parts.

Table 1. *Cont.*

HWT Products	Functional Mechanism	Total Cost (USD) Maximum Cost per Year	Efficacy (CFU/mL)	Storage and Capacity	Durability	Convenience of Use
DayOne Waterbag	Fill-add-close-mix-wait-drink, water needs to be used > 24 h. Most effective for highly turbid water. Used with P&G treatment packets (4 g packet contains Calcium Hypochlorite 0.546%, chlorine 2.17 ppm). Takes 25 min to purify with a 1.5 L/min flow rate. Treats 10 L of water.	300	6.0	YES (can hold 10 L of water).	The Waterbag provides a family of 4 with clean drinking water for up to 2 months and P&G packets lasts 3 years from the date of manufacture.	Simple to use-brief steps. No maintenance required. Minimal likelihood of recontamination Relatively long time to treat water-30 min. Not energy-deficient
AquaSure Tab 10	Double-layered tablets containing ferric sulfate and sodium dichloroisocyanurate (NaDCC). Ferric sulfate acts as a coagulant and flocculant. Floccules sediment settles at the bottom of the water vessel, NaDCC acts as a disinfectant. Each tab treats 10 L of water.	82	7.5	NO (does not include a safe storage container).	Aquasure Tab10 expires 3 years after the manufacture date	Residual protection against recontamination Need for multiple steps to use the product. Requires additional user support. No Maintenance required. Not energy-deficient
P&G Purifier of Water	P&G water purification technology: Quickly treats 10 L of contaminated water. It works in three ways: Coagulation, Flocculation and Disinfection. Add-Mix-Wait–Drink.	115	6.0	NO (does not include a safe storage container).	P&G packets lasts 3 years from the date of manufacture.	Residual protection against recontamination. Need for multiple steps to use the product. Requires additional user support. No maintenance required. Not energy-deficient
Waterlogic Hybrid	Electric water treatment device fitted with a carbon pre-filter and UV lamp. Water passes the pre-filter and UV lamp and is dispensed through a spout, the flowrate is 1.5 L per minute.	295	6.7	NO (does not include a safe storage container).	Long life filter and lamp only need one change per year.	Electricity required. Maintenance required. Reliable supply chain is required. Simple to use.

Based on the results from the epidemiological analysis, we found that, unsurprisingly, the number of recorded cases, incidence, and initial dose (i.e., dose capable of causing an infection before treatment) show a positive correlation with one another. In other words, the higher the infectious dose, the higher the recorded number of cases, and hence an increased level of cholera incidence. Our calculation of log10 reduction also shows that the final doses (CFU/mL) across all household water treatment technologies after treatment were virtually zero, which confirms the efficacy of these interventions in reducing the incidence of cholera. Thus, our results confirm that the final concentration of Vibrio cholerae across all treatment technologies was well below detection limits and could not cause a case of cholera infection.

The result to compare the cost of cholera treatment and procuring a household water treatment (HWT) product over one-year period has shown that the cost of cholera treatment is less expensive than 60% of the HWT products examined (Figure 1). The direct cost of cholera treatment based on the cumulative inflation rate of 44.3% equals USD 125.17. AquaPak, Solarbag, Aquasure Tab 10, and P&G Purifier of Water are the only products relatively cheaper than treating a mild or severe case of cholera infection.

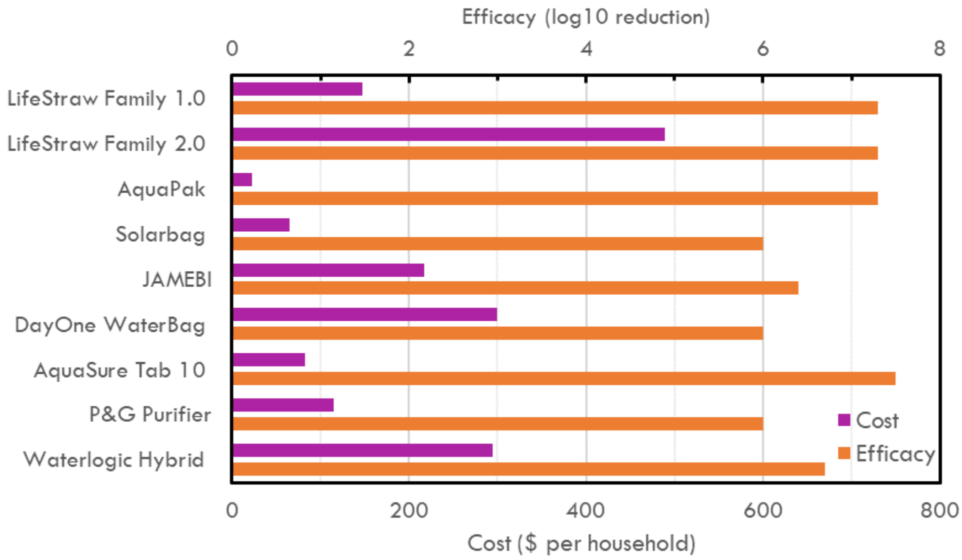

Figure 1. The cost and efficacy of HWT technologies. For comparison of costs, we estimate the average cost of treating an individual case of cholera to be USD 125. Efficacy represents the estimated reduction in pathogen concentration after adoption of a particular technology. A higher efficacy indicates a larger reduction in pathogen load.

We calculated affordability as the ratio of the HWT cost and the annual household income (Figure 2). As such, a lower percentage indicates a higher affordability. According to our research, the average rate of affordability for all Household Water Treatment products is less than 25% of the annual household income of low-middle income earning class. However, there are still significant disparities in affordability of the specific types of household water treatment products. Based on their functional mechanism, products that are classified as membrane filtration are the most expensive except for the LifeStraw Family 1.0 and LifeStraw Family 2.0 (19.9%). Products that function through the process of Flocculation-Disinfection-Filtration are the second most expensive; DayOne WaterBag (12.2%). The UV disinfection technologies are the third most expensive; Waterlogic Hybrid (12%). Products that treat contaminated water through solar/thermal disinfection and flocculation-disinfection are the cheapest products of these categories; AquaPak (0.9%), Solarbag (2.7%), AquaSure Tab 10 (3.3%), P&G Purifier of Water (4.7%), and JAMEBI Solar Water Pasteurizer (8.8%).

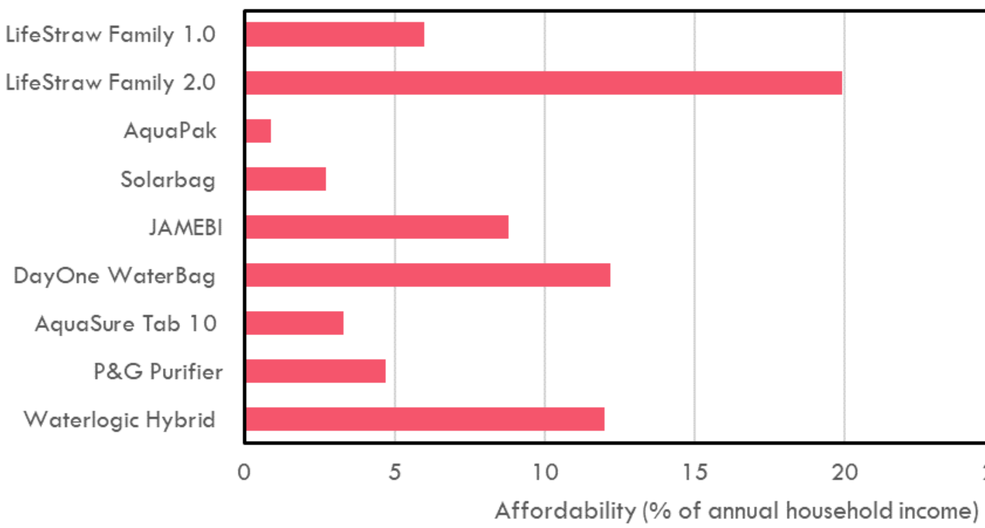

Figure 2. The average rate of affordability for all HWT products. A lower percentage indicates a higher affordability, as this is a smaller amount of a household's income.

The results of the study indicate that there is a narrow range in the efficacy of household water treatment technologies. Four treatment products have similar efficacy values of 7.3 CFU/mL (Figure 1). It showed that there was no significant correlation between cost and performance efficacy, indicating that more expensive HWT products tended to perform either more effectively or less effectively in terms of reducing *vibrio cholerae* load in water as compared to cheaper HWT products. Among the HWT technologies tested, Aquasure Tab 10 seems to have the highest performance efficacy of 7.5 CFU/mL and is one of the three cheapest HWT products. On the other hand, DayOne Waterbag was the third most expensive HWT product but had the lowest performance efficacy, with a value of 6.0 CFU/mL.

The total cost of adopting any HWT treatment technologies across sub-Saharan Africa if subsidized is relatively cheaper than constructing a centralized water supply infrastructure (Table 2). The estimated cost of constructing a centralized water supply infrastructure is USD 14.97 billion, which is almost twice the cost of financing the most expensive household water treatment technology (LifeStraw 2.0).

Table 2. Relative cost of universal HWT adoption and water supply infrastructure. Table compares the total cost of financing all HWT products in sub-Saharan Africa and the estimated cost of constructing a centralized water supply infrastructure (TCWSI) by the government.

HWT Product	Total Cost of Universal Adoption (Billion USD)
LifeStraw 1.0	2.51
LifeStraw 2.0	8.36
AquaPak	0.39
Solarbag	1.12
JAMEBI	3.70
DayOne Waterbag	5.12
AquaSure Tab 10	1.40
P&G Purifier of Water	1.96
Waterlogic Hybrid	5.04
TCWSI	14.97

4. Discussion

Cholera has been identified as a significant marker of inequity that disproportionately affects the poorest populations of a region [26]. The epidemiology, reservoir of the *Vibrio cholerae*, exposure pathway, and modes of transmission are highly connected with poverty. We infer that vulnerable populations are those that lack access to safe drinking water, health care services, good sanitation, and hygienic practices.

This study provides insight into the feasibility of adopting household water treatment technologies as a systemic intervention in reducing cholera burdens in high-risk communities of the sub-Saharan Africa region. The analysis examines the performance efficacy of different household water treatment products and their total cost of adoption while considering other factors such as durability, convenience of use, storage capacity, and mode of functionality. We find that using the most recent cholera outbreaks in sub-Saharan Africa provides a snapshot of the most probable outcome on the extent of reduction when household water treatment technologies are effectively adopted. We find that the evaluated HWT products have very high microbiological performance and can treat drinking water that is contaminated with high loads of *Vibrio cholerae*. The daily use of HWT products by households in cholera hotspot regions can virtually eliminate cholera infection. This implies that if HWT products were effectively adopted across sub-Saharan Africa, nearly all cholera transmitted through fecal-oral route will be prevented. By comparing all HWT products based on the convenience of use, mode of functionality and accessibility, we can rank products in descending order as categorized under solar/thermal disinfection, flocculation-disinfection, membrane filtration, and UV disinfection. Based on product cost we can also rank in ascending order as; AquaPak, Solarbag, AquaSure Tab 10, P&G

purifier of water, LifeStraw Family 1.0, JAMEBI Solar Water Pasteurizer, WaterLogic Hybrid, DayOne Waterbag, and LifeStraw Family 2.0, respectively. The socio-economic status of households is a critical factor in our study. The rate of affordability of the HWT products is an important determinant in the level of adoption across the sub-Saharan Africa region. The results on affordability show that the cost of procuring any of the HWT products is about 25% of the estimated average annual income of households in cholera hotspots. In the poorest countries in sub-Saharan Africa, households might have to spend 5% or more of their income on water. However, the poorest urban households and virtually all rural households, which constitute most of the population, can hardly afford to pay more than this amount [27]. Similarly, in Sub-Saharan Africa, poor families spend up to 5% of their total household income on water and sanitation, while wealthier families spend less than 1% of their income on these services [28].

This clearly implies that all households that reside in the cholera hotspots cannot conveniently afford it, given that there are other important household utility expenses. This indicates that most of the evaluated HWT products are unaffordable, and the need for subsidies to offset the cost are necessary for universal adoption. Comparison between the cost of treating a case of cholera in a household and the cost of adopting any of these technologies shows that the overall cost of treating a case of cholera is relatively cheaper than five out of nine HWT products (LifeStraw Family 1.0, LifeStraw Family 2.0, DayOne WaterBag, JAMEBI Solar water pasteurizer, Waterlogic hybrid). There is an inherent calculation of risk that each household weighs against the added expense of purchasing the HWT products. Thus, our results suggest that households perceive the risk to be low enough that it does not warrant the expense of purchasing a HWT product. However, the low cost of treatment does not ultimately imply that it is cheaper considering the rate of infectivity of cholera and exposure pathway. If a member of a household has cholera, there is a high probability that other household members may get infected as well, and this could increase the overall cost of cholera treatment while reducing household opportunities for earning income. A suite of socio-cultural factors can also exert great influence on the prevalent low level of adoption of these HWT products. The challenges include perception of water quality, education and awareness, access to technologies, cultural beliefs and practices, and gender roles. The main factors influencing water quality perceptions are drinking water organoleptic i.e., sensorial information from taste, odor, color. Certain people believe that when water appears clear and has no odor or taste it is safe for drinking [29]. This perception often makes it difficult for people to accept the need for water treatment technologies and lack of motivation to invest in water treatment technologies. Households with higher levels of education are more likely to adopt water treatment technologies than those with lower levels of education [30]. The availability and access to affordable and effective household water treatment technologies are critical determinants of adoption, and the reliable supply chain of these products to ensure consistent use is a limitation. In some cultures, boiling water is perceived as the only effective water treatment method, while in others, adding traditional herbs is perceived to purify water. Gender roles can also influence the adoption of water treatment technologies. In many households in sub-Saharan Africa, women are responsible for collecting water and managing household chores, including water treatment. Therefore, gender-sensitive approaches that involve women in the decision-making process and provide them with the necessary skills and resources to adopt and sustain water treatment technologies are crucial.

In most developed countries, households are largely dependent on centralized water supply systems as compared to developing countries where there may be a greater dependence directly on water sources such as rivers, streams, hand-dug boreholes, and wells. The biggest constraint that most developing countries have is inadequate infrastructural policies and lack of capital to finance the construction of centralized water supply infrastructure (TCWSI). Our results compared the total cost of financing all HWT products in sub-Saharan Africa and the estimated cost of constructing a centralized water supply infrastructure (TCWSI) by the government. The cost of financing a centralized water supply infrastructure is more than twice the total cost of financing the most expensive household water treatment product across sub-Saharan Africa. This finding implies that—in terms of upfront costs—investing in HWT products could be a more cost-effective solution for providing clean water to the people of sub-Saharan Africa. By promoting the use of HWT products, we can provide access to clean water while minimizing the financial burden on the government. Furthermore, the cost-effectiveness of HWT products is not limited to their lower cost. HWT products can also be implemented more quickly and with less disruption to local communities than centralized infrastructure projects. Additionally, HWT products can be tailored to meet the specific needs of different communities, whereas centralized infrastructure is often a one-size-fits-all solution. It is of no doubt that the CWSI serves as an important long-term intervention in reducing the risk of cholera outbreaks. However, infrastructure investments are large, lumpy, and infrequent; they often take more than one budget cycle to complete. Further, infrastructure assets require sustained preventive maintenance to ensure their upkeep and prevent deterioration. Another risk associated with CWSI is the possibility of re-contamination through water distribution and storage. Point of use household interventions are effective in reducing the risk of cholera re-contamination compared to big water supply infrastructure particularly in low and middle-income countries such as countries in sub-Saharan Africa [31].

In presenting our findings in this study, we acknowledge several limitations. The first is the underestimation of recorded cases of cholera; some cases are not clinically confirmed and as such cannot be reported. Second, the total cost of procuring HWT products was estimated based on the manufacturer's selling price, which may not be consistent with the actual retail price for these products. Third, to some extent there is likely under-representation of HWT products that are already adopted and in practical use in cholera hotspots. Fourth, we assume that the recorded cases were all transmitted through a fecal-oral route. Fifth, the budget of the TCWSI in sub-Saharan Africa is not absolutely accurate due to substantial inefficiencies such as lack of maintenance budget, inflation, and the hidden costs of labor and energy. Sixth, we assume that all individual's daily income is USD 2.15, which is the international poverty line due to the inconsistencies in the national income-level data for all countries in sub-Saharan Africa. The findings demonstrate opportunities for the long-term sustainable use of the HWT products; however, scalability depends on a strict adherence to correct use, which can be impeded by the lack of consistent supply of these HWT products.

5. Conclusions

Household water treatment technologies can be an effective intervention to reduce cholera burden in sub-Saharan Africa, especially in areas where access to clean water is limited. The cost-effectiveness and affordability of these technologies are important considerations for widespread implementation in the region. Performance efficacy studies have shown that various household water treatment technologies can effectively remove or inactivate *Vibrio cholerae* bacteria. However, accessibility remains a challenge as technologies may not be readily available or may require specific skills for proper usage and maintenance. Therefore, the implementation of these technologies should be accompanied by community education and awareness programs to ensure their proper and sustained use. Overall, the use of household water treatment technologies, tailored to the specific needs and challenges of the region, can contribute significantly to reducing the burden of cholera in sub-Saharan Africa.

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