

Household Drinking-Water Treatment and Safe Storage in Sub-Saharan Africa: Bridging the Gap between Efficacy and Sustained Use in Rural and Peri-Urban Communities

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Abstract

Unsafe drinking water remains a major driver of preventable waterborne disease and child mortality across sub-Saharan Africa. Household water treatment and safe storage (HWTS) interventions—including point-of-use chlorination, filtration, boiling, solar disinfection, and coagulants—offer proven microbial decontamination at the point of consumption. However, a significant gap persists between technical efficacy under ideal conditions and long-term sustained adoption in real-world settings. This narrative review critically examines empirical evidence published between 2020 and 2026 on HWTS efficacy, household recontamination dynamics, behavioral determinants, and implementation models across rural and peri-urban sub-Saharan Africa, with primary emphasis on Nigeria. Synthesised evidence demonstrates that while technologies such as silver-impregnated ceramic vessel filters, biosand filtration, and point-of-use chlorination achieve 2.0 to >4.0 log₁₀ microbial reductions in laboratory trials, real-world effectiveness is heavily compromised by post-treatment recontamination during storage (occurring in 42% to 78% of treated water samples) and rapid adoption decay. Key drivers of low sustained use include organoleptic aversion to chlorine taste, high recurring costs for commercial products, cumbersome daily operation, and lack of institutionalized governance. Cross-sectional and longitudinal data from Nigeria indicate that household water treatment practice remains below 16% nationally, with severe rural-urban and socioeconomic disparities. Sustainable progress requires transitioning from sporadic hardware distribution to multi-sectoral behavioral change strategies, microfinance-backed technology supply chains, community-led monitoring, and institutionalized national WASH policy integration.

Keywords: household water treatment and safe storage; microbial recontamination; Nigeria; Sub-Saharan Africa; sustained adoption

1 Introduction

Safe drinking water is a basic human right and a key factor in good public health, human dignity, and economic development. Despite the many international commitments to achieve universal, equitable access to sustainable and safe drinking water by 2030 (SDG 6), the burden of sub-Saharan Africa for waterborne infections and WASH-attributable morbidity remains the highest globally [1]. Millions of households in the region have unimproved or microbiologically contaminated drinking water sources such as hand-dug unprotected drinking water wells, rivers, streams, ponds, and shallow boreholes

that are not maintained [2, 3]. Microbial contamination, mostly due to the presence of both fecal indicator and coliform bacteria, is common in both rural agrarian communities and fast-growing informal peri-urban settlements [4] [5]. In Nigeria, the most populous country in Africa, national outcome routine mapping indicates that more than 68% of household drinking water samples collected at the point of use contain hazardous levels of faecal contamination (>0 CFU/100 mL) directly contributing to endemic diarrhoeal disease outbreaks, cholera epidemics and to reduce severe child undernutrition [6, 7].

Household Water Treatment and Safe Storage (HWTS) technologies make up a key first line of defense for waterborne enteric pathogens where there is no infrastructure, or where infrastructure is degraded or unreliable. HWTS includes all categories of point-of-use (POU) operations that purify water directly at the household level before it is consumed. The main HWTS modalities are the use of thermal boiling, chemical disinfection (liquid sodium hypochlorite, calcium hypochlorite or dichloroisocyanurate tablets), physical filtration (ceramic pot filter, ceramic candle filter, biosand filter or hollow-fibre membrane filter systems), solar disinfection (SODIS), and combined flocculant disinfection powder or plant-based biocoagulant (e.g., *Moringa oleifera* seeds) [8, 9]. When used and applied properly, these technologies achieve high levels of efficacy, routinely reducing pathogenic bacteria, protozoa and enteric viruses (pathogens) by 99% to 99.999% (>2.0 to >5.0 log₁₀ reductions) in the lab and controlled clinical trial settings [10,11].

Although there is strong biomedical and environmental health evidence for the technical effectiveness of HWTS technologies, a widespread 'efficacy-sustained-use gap' greatly restricts the public health reach of HWTS technologies in sub-Saharan Africa. Many intervention studies show that uptake of HWTS products can be high just after the free product distribution or a strong promotional effort, but uptake drops quickly after 3-12 months [3] [9]. In the real world, the rate of household uptake is generally less than 10–20% in vulnerable rural communities and this is likely to result in very small reductions in the community level burden of diarrhoeal disease [6, 12]. Moreover, and especially among households that regularly use POTW, water quality is often downgraded to unsafe levels prior to drinking due to post-treatment recontamination during storage and handling, and when cups are retrieved from the water container [13, 14]. An all-encompassing grasp of the technical product performance, dynamics of handling after collection, socio-economic constraints, organoleptic perceptions, and mechanisms of behavioural change is therefore of paramount importance.

The present narrative review critically and systematically integrates current literature on the effectiveness, implementation, dynamics of household recontamination, behavioral drivers, and models of HWTS in sub-Saharan Africa, particularly Nigeria, with the added goal of highlighting the strengths and weaknesses in the evidence. This review seeks to: (1) assess the technical effectiveness and operational compromises of key HWTS modalities; (2) explore real-world microbial and epidemiological results; (3) describe mechanisms of household safe storage failure and secondary recontamination; (4) delineate socio-demographic, economic, and behavioral determinants of sustained technology uptake; and (5) propose evidence-based policy, implementation, and research directions to narrow the gap between technical effectiveness and long-term community uptake.

2 Review approach

To synthesize multidisciplinary literature across environmental health science, environmental engineering, water microbiology, health economics and public health policy sub-Saharan Africa, a narrative review methodology was used. The literature published in the period of 2020-2026 was

identified, screened and integrated systemically. Searching was performed in a comprehensive electronic database search in PubMed, Web of Science, Scopus, Google Scholar, ScienceDirect and ProQuest Dissertations & Theses. The search strings included combinations of Boolean operators and key terms such as: ('household water treatment' OR 'point-of-use water treatment' OR 'HWTS' OR 'water disinfection' OR 'ceramic filter' OR 'chlorination' OR 'solar disinfection' OR 'boiling') AND ('safe water storage' OR 'recontamination' OR 'microbial water quality' OR 'Escherichia coli' OR 'coliforms') AND ('sustained adoption' OR 'sustained use' OR 'behavioral determinants' OR 'willingness to pay') AND ('sub-Saharan Africa' OR 'Nigeria' OR 'West Africa'). In addition, gray literature, such as technical outcome mapping reports from UNICEF, Nigeria Demographic and Health Survey (NDHS) data and the WHO/UNICEF Joint Monitoring Programme (JMP) datasets were included to provide policy-relevant context.

The inclusion criteria were: 1) household drinking water treatment, safe storage, or point-of-use water handling practices in a rural, peri-urban or informal settlement context in sub-Saharan Africa (with particular focus on West Africa and Nigeria); 2) water quality parameters (including E. coli, total coliforms, fecal streptococci, turbidity, residual chlorine, heavy metals), health outcomes (childhood diarrhoea morbidity, cholera incidence) or measures of household water handling adherence reported as primary empirical quantitative or qualitative data; 3) authorship by clearly identified researchers or recognized institutional bodies; and 4) the study was published in English between 2020 and 2026. Only studies that were done specifically at centralized municipal water treatment plants, industrial effluent processing, or that didn't have a specific household or community POWS evaluation were excluded.

Studies with ambiguous or unverifiable data, and those without a clear attribution of the authorship were not allowed to be cited in order to preserve methodological rigour and academic integrity. Thematic synthesis of extracted data were provided instead of stand-alone study-by-study summaries thus allowing direct comparison of technical performance, geographical variations and behavioral drivers. For the included studies, methodological designs were carefully evaluated for adequacy of sample size, rigor of sampling, detection methods of microorganisms (e.g., membrane filtration, MPN), and potential confounding factors. The methodological designs of the included studies (randomized controlled trials, prospective cohort studies, cross-sectional microbiological surveys, laboratory batch experiments, and qualitative focus group evaluations) were carefully assessed for adequacy of sample size, rigor of sampling, detection methods of microorganisms (e.g., membrane filtration, MPN), and potential confounding factors.

3 HWTS methods and their efficacy

The water treatment modalities are of varying type, and each has a different mechanism of pathogen inactivation or removal, are technically complicated to different extents, have different costs of treatment, and have different organoleptic effects on treated water at point-of-use. The inherent microbial effectiveness and physical functioning of these methods can be assessed under controlled laboratory conditions, and this is against which effectiveness in the field needs to be compared.

Thermal boiling is the oldest and most well-known household water treatment technique in Sub Saharan Africa. When water is brought to a rolling boil for 1 to 3 minutes [4, 12] boiling will produce complete microbiological inactivation of vegetative bacterial pathogens, viruses, protozoan cysts (including *Giardia lamblia* and *Cryptosporidium parvum*), and helminth eggs. Laboratory testing has shown that E. coli and total coliform counts are reduced by $>5.0 \log_{10}$ (99.999%), regardless of the

initial turbidity of the raw water. But, cooling and storage do not offer any chemical residual protection from post-treatment secondary recontamination when using boiling. Moreover, boiling consumes a significant amount of fuel such as wood, charcoal or kerosene and puts severe strain on the economy of low-income families and leads to environmental deforestation and indoor air pollution [4, 9].

Use of liquid solutions of sodium hypochlorite (e.g. WaterGuard) or calcium hypochlorite granules, or NaDCC (sodium dichloroisocyanurate) tablets is a globally recommended method of POU disinfection because it can provide a free residual chlorine concentration (FRCC) between 0.2 and 0.5 mg/L to prevent recontamination of the treated water during household storage [3] and [11]. In low turbidity waters (<5 NTU), chlorination is always able to provide 3.0 to >4.0 log₁₀ reductions (99.9-99.99%) of *E. coli* and *Vibrio cholerae* after 30 minutes of contact time [11,14]. The effectiveness of chlorine disinfection is drastically reduced in highly turbid waters with suspended organic particulate matter (SOPM) that demands high chlorine dose and protects microorganisms that are encased from the attacks of chlorine. In addition, chlorination is not very efficient at inactivating chlorine-resistant protozoan oocysts, like *Cryptosporidium*, and is often rejected due to organoleptic taste and odor complaints by consumers [11].

Physical filtration materials such as the ceramic vessel/pot filters and biosand filters offer continuous physical strain and biological filtration without affecting the taste of water. The locally made ceramic pot filters have pore size ranging from 0.6 to 3.0 µm which can effectively remove helminths, bacteria and suspended sediments [10]. The dual action decontamination is possible for modern ceramic filters impregnated or coated with silver nanoparticles (AgNPs) or colloidal silver which has slow release oligodynamic bactericidal action (Ag⁺ ion release) which interrupts the transport of the cell membrane and DNA replication of the bacteria [10]. The silver nanoparticles synthesized using the green technique, when incorporated into ceramic filters, have been shown to reduce *E. coli* by 3.8 to >4.5 log₁₀, remove *Vibrio cholerae* completely, and reduce turbidity to less than 1.0 NTU at flow rates of 1.5–2.5 L per minute in Nigerian communities [10]. Biosand filters (BSFs) are biological schmutzdecke maturation combined with a sand gradient filtration that results in 1.5-3.0 log₁₀ bacterial reduction with very good turbidity clearance, but it requires a bulky construction, a relatively high weight and the need to perform maintenance frequently, which restricts fast household mobility [13, 15].

Solar Disinfection (SODIS) is based on the synergistic bactericidal action of solar ultraviolet-A radiation (UV-A, 320-400 nm) and high thermal temperatures (>45°C) that cause damage to the structure of microbial cells. SODIS is found to provide 2.0 to 4.0 log₁₀ reductions in *E. coli*, *Salmonella enterica* and *Shigella* species for clear polyethylene terephthalate (PET) water bottles containing water with <30 NTU turbidity when they are exposed to direct sunlight for 6 hours (or 2 days when the sky is overcast) [16]. Isikhuemhen et al. [16] studied the efficacy of SODIS for drinking water samples from wells in the Southern part of Nigeria and achieved complete inactivation of coliform under peak solar irradiance of > 650 W/m². The bottles used for SODIS, however, have physical limitations due to their volume (1.5-2.0 L PET bottles), a lack of residual protection, weather dependence and severe turbidity limitations.

Primary pre-treatment and natural-based biocoagulants are used in turbid surface waters as either pre-treatment or standalone treatment. Inorganic aluminum sulfate (alum) instantly neutralizes the negative surface charge of clay particles, causing flocculation and sedimentation that lowers the turbidity of raw water by >90% and co-precipitates 1.0–2.0 log₁₀ of attached bacteria [8, 17]. The

natural biocoagulants come from crushed seeds of *Moringa oleifera*, *Cucurbit pepo* (pumpkin) and *Cicer arietinum* (chickpeas), which have dimeric cationic proteins with electrostatic destabilizing effects on suspended particles. *Moringa oleifera* seed powder at 50-150mg/L reduced the turbidity by 85-95% and bacterial load by 88-96% in turbid pond and stream water in Northern Nigeria; as reported by Garba et al. [8] and Oyeleke et al. [18]. Unrefined plant powders, however, leave behind some organic matter that can provide growth media for the re-growth of bacteria if the water is not chemically disinfected with another chemical, or kept for more than 24 hours. [8, 17].

Table 1. Key empirical studies on household water treatment and safe storage (HWTS) in sub-saharan Africa.

Study	Country	Study Design	Sample Size	HWTS Method	Key Quantitative Findings
Afolabi et al. (2022) [10]	Nigeria	Laboratory batch & field trial	45 ceramic filter units	Green AgNP-coated ceramic vessel filters	Achieved 3.8 to >4.5 log ₁₀ E. coli reduction; 100% <i>Vibrio cholerae</i> removal; reduced turbidity <1.0 NTU at flow rates 1.5–2.5 L/hr.
Amenu et al. (2021) [12]	Ethiopia	Cross-sectional survey & microbial analysis	384 rural households	Boiling, chlorination, safe storage	POU treatment practiced by 18.2% households; maternal education (AOR = 3.18) and wealth strongly predicted treatment adherence.
Bawa et al. (2021) [4]	Nigeria	Cross-sectional microbiological survey	120 household water samples	Boiling, alum coagulation	72.5% of stored household water samples contained fecal coliforms (>10 CFU/100 mL); post-collection recontamination in 65% cases.
CHoBI7 Study (2021) [19]	DR Congo / Bangladesh	Randomized controlled trial & mHealth evaluation	240 cholera patient households	Facility-initiated chlorination + mHealth reminders	Achieved >70% sustained water chlorination and safe storage compliance at 12-month follow-up vs 22% in control group.
Daniel et al. (2020) [11]	Sri Lanka / Sub-Saharan Africa	Prospective cohort study	210 households	POU chlorination (NaDCC tablets)	Achieved 3.2 log ₁₀ bacterial reduction in low turbidity (<5 NTU); adoption decayed from 85% at Month 1 to 28% at Month 6 due to taste objections.
Garba et al. (2022) [8]	Nigeria	Experimental laboratory study	36 water samples	<i>Moringa oleifera</i> seed biocoagulation	50–150 mg/L seed powder achieved 85–95% turbidity reduction and 88–96% coliform reduction in turbid surface water.
Isikhuemhen et al. (2021) [16]	Nigeria	Field experimental trial	50 well water bottles	Solar Disinfection (SODIS) PET bottles	Complete coliform inactivation achieved after 6 hours solar exposure (>650 W/m ²); constrained by 2.0 L bottle capacity and turbidity.
Kanyangarara et al. (2021) [20]	Nigeria	Nationally representative survey analysis	21,500 under-five children	Multi-level epidemiological modeling	Combined access to improved water and POU treatment reduced childhood diarrhoea odds by 38% (OR = 0.62, p < 0.001).

Study	Country	Study Design	Sample Size	HWTS Method	Key Quantitative Findings
Nnaji et al. (2021) [13]	Nigeria	Longitudinal water quality monitoring	150 households across 5 communities	Clay pots, buckets, tapped jerrycans	64% of pristine borehole water samples became microbially contaminated within 48 hrs storage; narrow-necked tapped jerrycans prevented re-contamination.
Ogedengbe et al. (2021) [14]	Nigeria	Comparative storage container trial	60 household storage vessels	Wide-mouthed buckets vs tapped jerrycans	Tapped jerrycans maintained <i>E. coli</i> <1 CFU/100 mL for 7 days; wide-mouthed buckets exceeded 100 CFU/100 mL by Day 3.
Omotosho et al. (2021) [21]	Nigeria	Multi-parametric water safety survey	100 source & 100 POU water samples	Groundwater extraction & household storage	82% of household POU samples contained <i>E. coli</i> >10 CFU/100 mL vs 45% at groundwater source; septic tank proximity identified as key risk.
Osuagwu et al. (2021) [22]	Nigeria	Storage duration experimental study	120 sachet water packages	Commercial sachet water storage (0–28 days)	Sachet water stored in direct sunlight experienced coliform growth (>25 CFU/100 mL by Day 28) and phthalate plasticizer leaching.
Suleiman et al. (2022) [17]	Nigeria	Cross-sectional survey & KAP evaluation	250 rural households	Chlorination, boiling, alum coagulation	68% of households abandoning chlorination cited recurring chemical cost and lack of rural stockists; alum preferred for visual clarity.
Yasin et al. (2020) [9]	Ethiopia	Cross-sectional community survey	422 households	Point-of-use chlorination (WaterGuard)	Consistently disinfected drinking water confirmed in only 14.7% households; maternal education (AOR = 3.18) was strongest predictor.
Yusuf et al. (2022) [23]	Nigeria	Comparative 14-day storage experiment	30 clay pots & 30 plastic containers	Unglazed clay pots vs plastic containers	Clay pots reduced water temperature by 3.5°C but accumulated internal wall biofilms causing bacterial re-growth; plastic containers had lower biofilm accumulation.

4 Real-world effectiveness: Water quality and health outcomes

Theoretically the microbial effectiveness of HWTS technologies that have been developed in a laboratory setting differ significantly from what is observed in the field when the technologies are operated by the householders themselves. Field evaluation studies conducted in Sub-Saharan Africa have all found that the health impacts of HWTS, including the mortality and morbidity reductions in childhood diarrhoea, dysentery and cholera are significantly weakened by poor adherence, improper handling and cleaning, ambient microbial exposure and the lack of consistent operation [3, 20, 24].

The findings from cross-sectional microbiological tests of PODW from rural and peri-urban communities in Nigeria highlight the extent of water quality degradation. Omotosho et al. [21] performed a multi-parametric drinking water safety assessment in Isale-Oyo, Southwestern Nigeria, with results

showing that 45% of the groundwater source samples complied with the WHO bacteriological guidelines for drinking water at time of extraction while 82% of the samples collected at the household point of use exceeded the *E. coli* guideline of 10cfu/100mL, considered a moderate to high health risk. Likewise, Tukura et al. [25] studied the increase in the counts of faecal coliform in the drinking water of the households of Akewu community in Ibadan, Nigeria, which was observed to increase by 3.4 fold (from 14×10^3 (CFU/100 mL) at source to 48×10^3 (CFU/100 mL) at storage) attributed to the improper manner of obtaining and storing the drinking water. Microbiological audits conducted in vended and stored drinking water containers in primary schools and households in the Federal Capital Territory (FCT) and Katsina State revealed *E. coli* contamination in more than 70% of vended and stored drinking water containers, which corresponded to the high prevalence of self-reported childhood diarrhoea [4, 26, 27].

The results of epidemiological studies assessing the health effects of HWTS interventions are not conclusive and vary. The studies by Kanyangarara et al. [20] using national existing demographic health data in Nigeria showed that children under five years of age in households using both an improved water source and verified POWT products had a statistically significant 38% lower prevalence of 2-week diarrhoea than children in households without POWT products (Odds Ratio [OR] = 0.62, 95% Confidence Interval [CI]: 0.51–0.76, $p < 0.001$). In communities with sporadic or improper use of HWTS (< 50% use daily), no statistically significant decrease in diarrhoeal disease was found [6, 20]. This is a non-linear association between compliance and health outcome, as occasional consumption of untreated contaminated drinking water (e.g., drinking untreated water 1 day per week) is sufficient to totally outweigh the health protection provided by HWTS during the remaining 6 days, due to the exponential dose-response curves of enteric pathogens such as *rotavirus*, *Cryptosporidium*, and *enterotoxigenic E. coli*.

5 Safe storage practices and household recontamination

Post-collection and post-treatment microbial recontamination during water storage is a critical vulnerability in the household drinking water supply chain in sub-Saharan Africa. Although water can be obtained from groundwater sources that are microbiologically safe, and can be effectively disinfected at the point of use, improper storage often contributes to the very fast deterioration of the water quality by the introduction of microorganisms, making it unsafe before use [13, 15].

There are several environmental and behavioral pathways for mechanisms of post-collection recontamination. Environmental recontamination is primarily associated with wide-mouthed unsealed storage vessels (e.g. open buckets, traditional clay pots and wide-bladed drums), with contaminated hands or dipping utensils (e.g. cups, ladles, bowls) during water extraction, airborne deposition of dust, contact with domestic animals, and the growth of biofilm on the internal surfaces of the vessels [13, 14]. In Southeastern Nigeria, Nnaji et al. [13] studied the dynamics of household water storage, and found that 64% of samples collected from water sources located in pristine deep boreholes were found to be contaminated with fecal coliforms after 24 to 48 hours of household storage. The concentrations of fecal coliforms rose from 0CFU/100mL in the borehole head to 38CFU/100mL in wide-mouthed clay pots and open buckets, mainly as a result of the extraction method of hand-dipping [13].

Physically designed storage vessels have a significant effect on microbial stability. Narrow necks and tight fitting screw caps with dispensing taps remove the chance of hand-to-water contact and stop secondary pathogen contamination from occurring [13, 14]. Ogedengbe et al. [14] compared the mi-

crobial recontamination level of water stored in narrow necked jerrycans with tap and wide mouth plastic buckets over 7 days and found that the microbial count of water stored in narrow necked jerrycan with tap was not exceeding 1CFU/100mL after 7 days, while the water stored in wide mouth plastic bucket had microbial count above 100CFU/100mL after 3 days. The materials used is also a key factor. The evaporative cooling effect of traditional unglazed clay water pots is an important property, where the water temperature of the pot is 3-5°C cooler than ambient temperature, which is highly appreciated by tropical households [23]. A comparative study conducted by Yusuf et al. [23] in Zaria, Kaduna State, found that clay pots (unglazed) kept cooler temperatures than the smooth plastic containers, but that the clay pots had high internal wall porosity that led to the growth of persistent bacterial biofilms during a 14-day period of storage as evidenced by the re-growth of coliform bacteria.

Commercially packaged sachet water ('pure water') and PET-bottled water are an emerging part of household water consumption in urban and peri-urban West Africa. Marketed as pure and packaged, water undergoes quality decay, during transit, distribution and retail storage [15, 22]. Osuagwu et al. [22] investigated the quality of sachet water after varying storage period in Nsukka Zone of Enugu State and found that sachet water stored in open direct sunlight at ambient temperature for longer periods (30–35°C) suffered from severe microbial deterioration. An increase in coliform counts from undetected on Day 0 to >25 CFU/100 mL on Day 28 coincided with plasticizer leaching from high-density polyethylene sachet films (phthalates) [22]. Likewise, Okeke, et al [28] and Ojile, et al [29] reported high bacteriological contamination in stored sachet and vended water of Port Harcourt and Bayelsa State respectively, and this improper stored water under ambient temperature affects its safety, as the commercially packaged water is vended.

6 Determinants of adoption and sustained use

The path from technology awareness to long-term use of HWTS within the household is determined by a complex interplay of socio-demographic, economic, psychological, structural and organoleptic factors. The knowledge of these behavioural determinants is essential to the development of intervention models which have long-term public health impact.

Across sub-Saharan Africa, the most consistent structural factors associated with HWTS adoption are socioeconomic status, wealth and maternal education. According to the national survey data in Nigeria households in the highest wealth quintile are more than 4.2 times likely to practice point of use water treatment as households in the lowest wealth quintile (OR = 4.25, 95% CI: 3.10–5.82, $p < 0.001$) [6, 7]. With the financial liquidity that comes from higher household income, more people will be able to afford to buy HWTS consumables and safe storage vessels. More people will be able to afford to buy HWTS consumables (chlorine tablets, liquid hypochlorite or replacement filter cartridges) and safe storage vessels, due to the financial liquidity provided by higher household income. There is a strong independent effect of maternal education: secondary and tertiary education are associated with higher health literacy, awareness of risk of microbial contamination and higher self-efficacy in operating HWTS [9, 12, 30]. Among the three, the variables that were associated with consistent household water chlorination were maternal education (AOR = 3.18, 95% CI: 1.84–5.50, $p < 0.001$) in Gibe District, Ethiopia.

Two operational challenges to sustained technology use are economic affordability and supply chain continuity. Households can use HWTS products during promotional pilot trials or during disaster relief operations without cost, but their uptake declines after a period of free distribution when the

households have to buy replacement consumables at commercial retail prices [3, 17]. Suleiman et al. [17] conducted a survey of household water treatment practices in Zamfara State, Nigeria and found that more than 68% of households that stopped using chlorination reported that the high and frequent cost of liquid chlorine bottles and the lack of people who sell chlorination products in the rural areas were the main reasons for abandoning them. Limited access to water treatment supplies in rural agricultural regions results in households not always being able to access water treatment supplies within reasonable distance.

The organoleptic properties, such as taste, odor and visual clarity have a strong psychological effect on consumer acceptance. The very medicinal taste and smell of free residual chlorine can cause a high level of resistance from the chemical chlorination interventions, a resistance which consumers often associate with chemical contamination or bleach toxicity [11]. Other technologies that improve visual water clarity without changing taste like ceramic filters, biosand filters, and alum coagulation on the other hand have gained higher satisfaction and user preference as it does not impact on the taste of the water [10, 17]. In addition, compliance is determined by the effort and convenience of daily operations. Abandonment rates are higher for technologies that involve complex steps (e.g. boiling water on woodstoves, waiting 6 hours for bottle solar exposure from SW, or multi-step filtration) than for others that are passive or involve less effort.

7 Implementation strategies and programme approaches

HWTS scaling up efforts have shifted from past maternal-driven distribution of free products to institutionalised, market-based and community-driven models in sub-Saharan Africa. Comparative effectiveness evaluations are essential for creating sustainable WASH programs.

Traditionally, hardware distribution campaigns have been a common strategy in public health and non-governmental organizations, especially in times of acute cholera outbreaks or humanitarian crises. Although free distribution appears to create a short-term coverage, systematic studies show that it does not promote long-term behavioral change, ownership or the development of commercial supply chain [7, 31]. After the end of the emergency relief programs, the usage of household equipment drops sharply and the equipment deteriorates because of the lack of maintenance and spare parts. To overcome these limitations, market-based approaches—such as micro-franchising, targeted smart subsidies, and commercial retail distribution—have been introduced. The use of local retail outlets and microfinance institutions as outlets for promotional messages has proven to have a higher sustained uptake rate, as it creates viable commercial distribution channels for social marketing campaigns such as subsidized commercial product delivery (brand name chlorine bottles or ceramic filters) [1, 11].

Community-led and health facility initiated behavioral change interventions have been shown to be more effective at achieving sustained technology uptake. The participatory hygiene triggering approach combined with HWTS and safe storage promoting is embedded in the community-led total sanitation (CLTS) frameworks and utilizes concepts of social norms, community pride, and peer accountability to facilitate community-wide change [7]. In addition, there is an exciting model for vulnerable population mobilization via targeted health facility-initiated interventions, like the Cholera Hospital Based Intervention for 7 Days (CHoBI7) mHealth program [19]. The CHoBI7 successfully improved the uptake of chlorination and safe storage practices to >70% in households, through the introduction of bedside counselling, distribution of starter HWTS kits, and mobile phone voice and text messaging to caregivers of acute diarrhoea patients upon discharge, during a 12-

month follow-up period [19]. Combining mHealth nudges at health system points of interaction is a very scalable approach to strengthening HWTS practices.

8 Evidence from Nigeria, research gaps and future research agenda

A case study of Nigeria is informative in studying HWTS dynamics in sub-Saharan Africa. Nigeria, with a population of over 220 million people, has very high ecological diversity ranging from the arid Sahelian area in the north to dense tropical rainforests and mangrove swamps in the south, and very pronounced socioeconomic stratification, contains all the multiple challenges of household drinking water security [6] [7].

Despite the national average of 67% access to improved water source (mostly deep borehole without pipes and protected well), fewer than 14% of Nigerian households report always treating water before consumption [6, 7]. This creates a paradox, as the 2021 national WASH outcome mapping data shows that water treatment practices are showing significant improvement, whereas the 2024 NDHS data shows limited improvement in water treatment practices. There are huge geographical and socio-economic differences in the practice of POU treatment. In rural agricultural areas of the North-East and North-West geopolitical regions, household water treatment rates are below 4% while in urban areas of the South-West, the rate is 24% [6] [17]. Additionally, more than 68% of the household point-of-use drinking water samples collected from all 36 states were contaminated by fecal samples (>0 CFU *E. coli* / 100 mL) indicating that simply switching to improved extraction sources is not sufficient to ensure microbially safe drinking water at the point of use [6, 7].

National findings are also supported by relevant region specific empirical studies in Nigeria which focus on localised environmental threats. The high water table in Northern Nigeria (Kano, Katsina, Borno and Kaduna states) is highly polluted with faeces from open defecation, pit latrines, and animal grazing [4, 26, 27] leading to widespread faecal contamination of shallow hand dug wells and boreholes. Traditional plant-based coagulants (*Moringa oleifera*) and alum are sometimes used for removal of turbidity in rain-fed turbid surface water but the use of chemical disinfection is uncommon [8, 17]. Rapid informal urbanization has resulted in significant contamination of groundwater by unlined septic tanks leaching directly into shallow aquifers in Southwestern Nigeria (Lagos, Oyo, Ogun and Ondo states) [21] [25]. Groundwater salinity and high concentration of industrial contaminants (heavy metals) in crude oil released into the ground near the oil-producing Niger Delta region (Bayelsa, Rivers, and Delta states) in addition to the heavy bacteriological pollution of the water sources makes the water they tap into very unsafe and leads people to drink commercially sold sachet water which is frequently recontaminated during the retail sale. [5, 13, 29]

While the knowledge base on HWTS is expanding, there still are many gaps in sub-Saharan Africa. First, long-term prospective longitudinal cohort studies (longer than 24 months) assessing technology adherence, maintenance decay and health outcomes in a non-trial, real-world environment are extremely limited. Secondly, there is a critical need to have toxicological and microbiological assessments of plant-based biocoagulants (*Moringa oleifera*, *Cucurbita pepo*) standardized and with regard to residual organic matter dynamics, storage shelf-life and combination with secondary chemical disinfectants. Third, research on health economics assessment on willingness-to-pay (WTP) by households, microfinance credit instruments, and optimal subsidy structure for HWTS hardware in low-income informal settlements is still in its early stages. Thirdly, the dynamics between the performance of HWTS and the climate induced extreme weather events (flooding, droughts) in emergency displacement contexts needs careful empirical research.

9 Conclusion and recommendations

To bridge the efficacy–sustained use divide in household water treatment and safe storage in the rural and peri-urban sub-Saharan African context, strategies need to transcend the individual technology distribution to multi-sectoral and integrated approaches. Although HWTS technologies are proven to have the ability to achieve microbial purification, real-world public health impacts are highly limited due to post-collection recontamination, cost, organoleptic resistance, and institutionalized governance issues. Evidence-based recommendations are organized by policy, practical implementation, and research areas with a view to advancing SDG 6 in a sustainable way.

9.1 Policy recommendations

1. **Institutionalize HWTS within National WASH Frameworks:** Federal and state ministries of water resources and health must formally integrate HWTS and safe storage promotion into national WASH sector policies, establishing dedicated budgetary lines for point-of-use chlorination and ceramic filter subsidies targeting vulnerable rural and informal settlement populations.
2. **Enforce Point-of-Sale Quality Surveillance for Packaged Water:** Regulatory agencies (e.g., NAFDAC and SON in Nigeria) must establish routine microbiological monitoring of commercial sachet and vended water at retail points, enforcing strict thermal protection standards during transport and storage.
3. **Implement Environmental Sanitary Buffer Zones:** Local planning authorities must strictly enforce a minimum 30-meter sanitary distance between shallow groundwater wells/boreholes and septic tank soakaways or pit latrines to attenuate subsurface microbial contamination.

9.2 Practical implementation recommendations

1. **Transition to Community-Led and Market-Based Distribution:** Program implementers should replace short-term free product distribution with sustainable, market-based supply chains, engaging local microfinance groups, female health entrepreneurs, and retail stockists to ensure continuous consumable availability.
2. **Institutionalize Health Facility-Initiated mHealth Promotion:** Scale up targeted mHealth behavioral programs (modeled on CHoBI7/PICHA7 frameworks) that initiate WASH counseling at healthcare facilities for mothers of acute diarrhoea patients, reinforced via automated mobile voice and text reminders.
3. **Promote Narrow-Necked Tapped Safe Storage Vessels:** Mandate that all HWTS promotional packages include narrow-necked, tightly capped safe storage vessels equipped with dispensing taps to completely eliminate hand-to-water contact during extraction.

9.3 Future research recommendations

1. **Conduct Multi-Year Longitudinal Compliance Studies:** Researchers should execute prospective cohort studies tracking household HWTS adherence, filter replacement cycles, and child health outcomes over 24 to 36 months under non-trial field conditions.
2. **Standardize Plant-Based Biocoagulants:** Environmental health scientists should optimize and standardize *Moringa oleifera* seed extraction and dosage protocols, evaluating toxicological safety, shelf-life, and combination with secondary chemical disinfectants.

3. **Evaluate Willingness-to-Pay and Micro-Credit Instruments:** Health economists should perform incentivized willingness-to-pay experiments to determine optimal pricing structures and evaluate micro-credit mechanisms for HWTs technologies in low-income rural communities.

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