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Application of Integrated Solar-Powered Ultraviolet Radiation and Sand Biofiltration Techniques in Rural Water Treatment: A Review

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Abstract
Access to clean water is still an issue all over the world, and in the context of rural and peri-urban areas of sub-Saharan Africa, it is a matter of grave concern due to widespread contamination of shallow wells and surface water resources by sewage from abattoirs and poultry farms. Commonly available technological solutions for rural water treatment are often very costly, energy-intensive, and technically demanding. This paper reviews the prospects of using sand-based biofiltration (bio-sand filtration) in combination with solar ultraviolet-C (UV-C) disinfection as a multi-barrier engineering solution to access safe water in rural Africa. The basics of sand-based biofiltration, including principles of schmutzdecke formation, pathogen removal kinetics, and hydraulic design are covered together with the basics of photochemical action of UV-C radiation, its dosimetry and limitations due to turbidity. The current state of development of engineering designs was reviewed, particularly the Centre for Affordable Water and Sanitation Technology (CAWST) Version 10 bio sand filter, biologically active carbon media in filters, and sizing solar photovoltaic (PV) power systems to operate UV lamps. Pilot field tests have demonstrated that the technology allows achieving more than 99.99% removal efficiency of bacteria, reduction of turbidity down to 1 NTU, and 40 mJ/cm² irradiance using a 10-16 W lamp and a 100 W PV module. Problems and perspectives of the application of the technology in Uganda with respect to water scarcity, industrial pollution, availability of solar radiation, and appropriate-technology infrastructure are discussed. This paper discusses the potential of Bio-sand filtration (BSF) with solar UV-C disinfection in terms of advancement of Sustainable Development Goal (SDG) 6 in rural Uganda.

Keywords: *Biofiltration; poultry and abattoir effluent; rural water treatment; solar power; UV-C disinfection; waterborne diseases.*

1.0 Introduction

The global water crisis largely targets dispersed communities and rural areas in developing countries, whereby an estimated 884 million people lack improved sources of drinking water [1]. People in those regions are more likely to experience increased risks of waterborne illnesses such as diarrhoea, cholera, and typhoid as a result of utilization of surface water sources and shallow wells [2]. Such sources of water are increasingly being contaminated due to increased human activities such as rapid industrialization, intensification of agricultural activities and poor management of wastes [3]. In countries such as Nigeria, studies conducted in various regions have demonstrated high levels of groundwater pollution from the effluents of abattoirs and intensive poultry production with infiltration of faeces and chemical effluents in the shallow aquifer [4].

Poultry and abattoir effluents are known to contain significantly high amounts of COD and BOD, suspended solids, fats, oils and grease, nitrogen and phosphorus, heavy metals, veterinary antibiotics and pathogenic micro-organisms such as faecal coliforms, Escherichia coli, and Salmonella [5]. Such effluents lead to depletion of the dissolved oxygen in the receiving waters, eutrophication and contamination of shallow groundwaters through leaching and runoffs, resulting in adverse effects on the environment and public health [6]. Some studies carried out in sub-Saharan Africa, have revealed that about 80 percent of the shallow wells in 300 meters radius of poultry facilities had significantly high microbial contamination, with compliance dropping to as low as 5 percent during the rainy season [7].

Point-of-use (POU) water treatment by households has been advocated by WHO as the quickest method to improve public health through provision of clean drinking water [8]. Among the POU devices that are widely recommended due to cost-effectiveness and ease of construction using local materials is the Bio-Sand Filter (BSF), which is the intermittent version of Slow Sand Filtration (SSF) technique [9]. The Bio-Sand filter can effectively remove about 99 percent of bacteria and considerably reduce turbidity; however, it may not be effective in elimination of viruses with removal efficiency going below 70 percent [8]. This paper explores the application of this technology as an engineering contribution to rural water sanitation through the examination of theoretical principles, technological development, local examples, and implementation possibilities in sub-Saharan Africa.

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2.0 Theoretical Study

2.1 The Schmutzdecke and the Mechanics of Biofiltration

Biofiltration is a water treatment method that uses a conventional granular filter media to filter both the dissolved organic material and the fine particulate materials through microbial breakdown. It is just like the slow sand filtration since it uses biological processes to break down suspended and dissolved organic materials [10]. However, unlike the rapid granular filtration, it does not use physical filtering. Biofiltration is considered a sustainable engineering technology since it reduces the amount of chemicals used as disinfectants, hence reducing the formation of carcinogenic disinfection by-products (DBPs) (ref).

The Biological Slow Filtration (BSF) system is different from the traditional rapid filtration process since it depends on the schmutzdecke, which is a biologically active layer that develops at the contact point between the sand and the water above [11]. The formation and working of this ecosystem, which is made up of algae, bacteria, and protozoa, takes 10 to 30 days and acts as the main source of pathogen elimination [4]. One of the features of sand biofilters is the development of biofilms that develop on the surfaces of the sand particle and include a diversity of microbes such as bacteria, protozoa, and fungi to break down organic pollutants and pathogens. Empirical data have shown that biofilm activity on sand media can remove BOD and COD at 76.9% and 73.5%, respectively [14].

There are four mechanisms that lead to pathogen removal in the biofiltration process. Firstly, the mechanical straining happens where pathogens and particles bigger than the pores of the sand are physically filtered; this increases when the schmutzdecke ages, hence decreasing the size of the pores [13]. Secondly, adsorption involves the trapping of microorganisms and organic materials on sand particles or the zooglea biofilm using electrostatics, Van der Waals forces, and biological interactions [14]. Thirdly, biological predation involves the active consumption of the pathogens by the diverse schmutzdecke community, especially the protozoa. Lastly, natural die-off occurs as a result of nutrient deficiency, reduction of dissolved oxygen in deep sand layers, and unfavourable temperature conditions [13].

Engineering studies show that sand grain diameter and time interval are the important performance criteria. The finer sand with the effective size, d10 = 0.15–0.17 mm exhibits the better bacterial and viral removal compared to the coarse filter media because of the long contact time and the low pore velocity. Decrease in d10 from 0.52 to 0.17 mm results in the 0.16 to 0.30 log unit increase in the indicator bacteria removal [8]. Hydraulic loading rate of 0.1–0.3 m/h allows obtaining excellent biological treatment due to the pathogen reductions exceeding 5-log10 for E. coli bacteria [14]. It is necessary to choose the uniformity coefficient (d60/d10) within 1.5–2.5, since a lower value improves the porosity and provides higher hydraulic residence time [14].

2.2 Hydraulic Design of the Bio-Sand Filter

The hydraulic design of the BSF governs the balance between contact time and throughput. The CAWST Version 10 configuration operates at a filtration rate of 400 $L/h/m^2$, down from 600 $L/h/m^2$ in Version 9, achieved by reducing the reservoir volume so that it approximates the pore volume of the sand bed rather than exceeding it [1]. This reduction reduces the maximum head driving flow through the bed by 37% [1] and along with the hydraulic loading rate for effective biological treatment of 0.1–0.3 m/h [14] keeps the superficial velocity below what would cause the schmutzdecke and deeper sand layers to short circuit the bed to the outlet. Since BSF is dosed intermittently, so it cannot be hydraulically coupled directly with the downstream UV-C stage, which must be dosed continuously to achieve the design retention time. The sequential arrangement thus needs an intermediate break or an equalisation tank between the BSF outlet and the UV unit inlet that the DC pump feeds at a set flowrate [15]. This buffer separates the batch hydraulic function of the filter from the continuous flow function of the UV chamber, and the volume of this buffer should be calculated to contain about one dose cycle of BSF effluent so that the operation of the filter pump (and therefore the UV dose) will not be interrupted between fill events.

This hydraulic design is a compromise, as both flow capacity and biologic performance are to some extent inversely related to each other throughout the filter's operating cycle. Over this period of 10-30 days, maturation of the biofilm removes the majority of pathogens, but at the same time it also gradually clogs the pores and decreases the maximum attainable flow rate, which increases the processing time per dose. The restoration of hydraulic capacity involves periodic disruption and skimming off of the top few centimetres of the sand bed, which removes the most physically active layer of the schmutzdecke, so the time between biofilm disturbances needs to be sufficient to allow a new biolayer to form before it is disturbed again, but not long enough for the pause period to be inconvenient for domestic use [8]. It is important to maintain this balance as much as its sand depth or grain size is important, it is the BSF's design specification.

2.3 Kinetics of Ultraviolet Radiation Disinfection

The mechanism of ultraviolet disinfection is photochemical and involves the disruption of nucleic acid of microbes when irradiating with UV light (254 nm). The photons absorbed by the DNA of microorganisms lead

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to formation of pyrimidine dimers, specifically thymine dimers. These dimers cause changes in the structure of DNA preventing its disintegration during replication [2]. Hence, the organism becomes inactive; although it will be able to perform some metabolic reactions such as respiration, it cannot reproduce anymore causing infections [16]. Research indicates that approximately 100 dimers per chain are required to reach this inactivation threshold in many pathogens [15].

There are three major responses of microorganisms to UV light which include the shoulder phase (the moment when inactivation begins after DNA repair occurs or several "hits" happen); the semi-log phase when the rate of inactivation increases proportionally to the dose of UV and the saturation phase (when rates decrease because of UV resistance or shielding effects). The Series-event Model is one of the approaches that is used to estimate the rate of disinfection and involves the accumulation of DNA damage up to the moment of inactivation of the organism. There is a more sophisticated phenomenological equation that correlates the rate of the reaction with the concentration of cells and the Local Volumetric Rate of Photon Absorption (LVRPA) allowing to take into consideration the inhomogeneity of radiation fields [18].

The problem of turbidity shielding is the primary limitation for UV disinfection systems since the particles suspended in contaminated water protect microorganisms from UV rays making it necessary to conduct pre-treatment [2]. Rural areas of Africa, where the initial turbidity of water caused by agricultural and slaughterhouse waste reaches more than 30 NTU [18], require pre-treatment of the water. Pre-treatment with biofiltration reduces the turbidity of the water to less than 5 NTU, the maximum allowed for UV exposure, and it is possible to obtain up to 0.35 NTU in optimised integrated systems [16]. The dose of 12 mJ/cm² provides a 4-log reduction of E. coli, while the regulatory standards provide 40 mJ/cm² as the standard dose for drinking water [19].

The repair processes by which microbes can be repaired need to be taken into account, such as photo-reactivation and dark repair processes. There are some microbes that make use of photolyase enzymes that are triggered by the UV-A wavelength from sunlight to repair the damage caused by the thymine dimers to the DNA structure [20]. Hence, it is vital that the multiple barrier strategy be used in which the biological predation reduces the microbial number that needs to be destroyed at the UV stage [21]. The use of solar energy to generate UV lamps will make this method of disinfection sustainable.

3.0 Integrated System Configuration

The engineering of integrated rural water treatment system uses a multiple barrier approach that involves the combination of biological filtration with ultraviolet (UV-C) light exposure for pathogen removal and inactivation [21]. The design is geared toward solving rural water quality problems, namely turbid water and faecal contamination arising due to agriculture runoff or abattoir effluent [2].

The first stage in the design involves a Bio-sand Filter (BSF) or Household Slow Sand Filter (HSSF) to serve as a key pre-treatment step [21]. The current designs use the CAWST Version 10 which improves hydraulics with increased sand bed to 55 cm and proportional reservoir size to the pore volume with the aim of maximizing biological residence time [1]. More sophisticated systems incorporate Biologically Activated Carbon (BAC) or Granular Activated Carbon (GAC) filters downstream to remove dissolved organic carbon and other chemicals like ammonium [21]. The BSF uses the diffuser plate for protection of the schmutzdecke from disruption during water introduction. A supernatant water layer of 5 cm is maintained on top of the sand layer to maintain aerobic biological conditions and prevent drying of the biolayer.

The second stage is represented by a UV disinfection system and is necessary since biofilters are unreliable for eliminating virus pathogens [8]. For prevention of turbidity shielding, the biofilter needs to lower turbidity levels to less than 5 NTU and ideally less than 1 NTU to maintain high UV transmittance [21]. The UV unit can be designed as an annular flow through reactor in which the treated water flows around a germicidal lamp producing radiation with wavelength of 254 nm to disrupt microbial DNA [17]. Dose of 40 mJ/cm² is the minimum UV exposure required to inactivate the vast majority of bacteria, protozoa, and viruses [15].

These systems in remote African locations lacking electricity grid connection can be powered using solar power [21], [11]. A typical tropical region system design involves 100 Wp photovoltaic (PV) panel along with battery storage capacity to operate the 10–16-watt germicidal lamp [16]. A DC pump providing 3 L/min flow rate is needed to maintain the minimum hydraulic retention time of 9 seconds inside the UV chamber at UV intensity of 4.5 mW/cm² [15]. Engineering calculations conducted in relation to the Musi River showed that in 60 minutes, solar-powered system can reduce E. coli concentration in filtered water by 6-log factor [11]. The final design component is a storage tank with a lid and tap to minimize the post-treatment contamination risk [23].

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4.0 Engineering Inputs and Design Progress

4.1 Transition to CAWST Version 10

The transition from the Version 9 to the CAWST Version 10 (v10) Bio Sand Filter has represented a significant advance in engineering by including a substantial increase in emphasis on hydraulics in order to improve the efficiency of microbial filtration. One of the alterations introduced in the design has been associated with the increased depth of the sand layer up to 55 cm instead of 45 cm, which resulted in the increase in the adsorption surface area by 22%, as well as extended contact time in order to ensure efficient virus filtration [1].

The engineering analysis has shown that the reservoir volume in Version 9 BSF is often higher than the sand pore volume, which causes the issue of the majority of the added water being flushed through the filter without having enough time to stay in the filter to experience biological predation. In the new design, the reservoir volume has been reduced to 12 L in order to match the increase in the pore volume and, therefore, to ensure that the whole added water will be retained inside the sand pores during the pause period and achieve maximum biological predation and decomposition of pathogens. As a result, the maximum head pressure has been reduced by 37%, along with decreasing the filtration rate down to 400 $L/h/m^2$ from 600 $L/h/m^2$, which has increased the efficiency of MS2 virus removal in laboratory conditions to 99.99% [1].

4.2 Improvements to Nutrients and Media

Biofilters are now moving from depending on sand to using Biologically Activated Carbon (BAC) and Granulated Activated Carbon (GAC) [16]. GAC has been found to be an excellent growth medium as its porous surface can hold four to eight times more biomass than sand or anthracite but also protects microorganisms from shear stress [10]. The exhausted GAC filter after losing its adsorption capacity after about two to three months still works as a BAC filter where biofilm formed continues with biodegradation.

The metagenomics study based on 16S rRNA genes has revealed that BAC medium is able to host the specific nitrifiers, including nitrifiers belonging to the phylum Nitrospirae, like Nitrospira and Nitrosomonas oxidising ammonia and nitrite into nitrate [16]. Integrated pilot-scale units containing BAC column filters have been successful in removing 85.71% of ammonium and about 45% of dissolved organic carbon (DOC). It has also been demonstrated in studies that phosphate addition can optimise such filters resulting in increased DOC removal from 12% to 23% due to enhanced growth of native bacteria [10]. In case of contaminated water having high organic loading from poultry and abattoir wastewater, integrated GAC and sand biofilters have reported 79.2% and 82.6% ammonia nitrogen and turbidity removals [10].

4.3 Solar-UV Optimisation

Calculation of the Volumetric Rate of Photon Absorption (VRPA) of the UV reactor has been improved to provide reliable disinfection in a decentralised manner. The use of VRPA makes it possible to develop annular reactors taking into consideration the lack of uniformity in the distribution of the radiation field and concentration of the active cells [17], which ensures the fluence of UV sufficient to penetrate the water column under varying weather conditions provided that the pre-treatment BSF stage has reduced the turbidity of the water below 5 NTU [10] in order to avoid the shielding of pathogens by particles.

It is typical to use 100 Wp photovoltaic (PV) module and storage battery for powering a 10–16-watt UV-C germicidal lamp in the system to be used in remote tropical areas [16]. Studies conducted in laboratory and field conditions on the Musi River showed that 60 minutes of solar-powered exposure to the UV-C radiation at 254 nm results in high-level inactivation, including 6-log reduction of E. coli in pre-filtered water [11]. The system consisting of pre-treatment of the water by BSF to reduce turbidity and organic shielding followed by solar-powered UV disinfection provides an effective treatment chain.

5.0 Adoption in Uganda: Contributions, Prospects, And Challenges

5.1 Prospects for Adoption

The implementation of integrated bio-sand filter (BSF) and solar ultraviolet-C (UV-C) disinfection system is of critical geo-graphic importance in Uganda. The country has over 46 million people with most of them living in rural areas, and the persistent problems of providing safe water to the population remain. Only 22% of the rural population has access to basic water services [24]; implementation of the National Water Policy which aims for safe water for 77% of the rural population by 2015 is not consistent across districts [25]. [26] conducted recent field evaluations in various households in the rural community of Uganda which found that households continue to use unprotected water sources and are highly vulnerable to waterborne pathogens. The variability of raw water quality is further highlighted by the fact that from 6.4 NTU at the landing sites of Lake Victoria, the turbidity recorded at the landing sites of Lake George is 175 NTU during the wet season [27]. Unprotected shallow wells, springs and surface water sources are especially relied on by communities in agricultural areas around Lake Victoria, the Nile Basin, and the Albertine Rift, and areas of livestock intensification in the northern and eastern regions of the country, are vulnerable to being contaminated by poultry activities, abattoir and

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uncontrolled disposal of effluents [24]. These activities generate large concentrations of faecal coliforms, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in local water bodies [27]. There are a few small-scale research projects that offer a technical and a social argument for implementing this multi-barrier technology.

Table 1 shows Uganda-specific findings within the most recent nationally representative data on drinking water and sanitation service levels.

Table 1: Key WASH coverage indicators for Uganda, 2024

Indicator	National	Urban	Rural
Access to improved water sources	81.1%	86.6%	77.4%
Safely managed water services (SDG 6.1)	~8.8%	25.7%	3.6%
Water on premises (household connection)	~10%	Higher	<10%
Improved sanitation facilities	43.1%	60.9%	31.8%
Safely managed sanitation services	Low	40.7%	8.2%
Open defecation prevalence	~6%	Lower	Higher
Handwashing facility with soap and water	24.3%	Higher	Lower
Proper solid waste disposal	~8%	~1.7%	~1.7%

Source: UBOS, 2025

Nationally, only 8.8% of Ugandan households have safely managed drinking water, and open defecation is higher in rural areas as compared to urban areas, but this national picture masks sharp disparities by place of residence that are directly relevant to the communities discussed above.

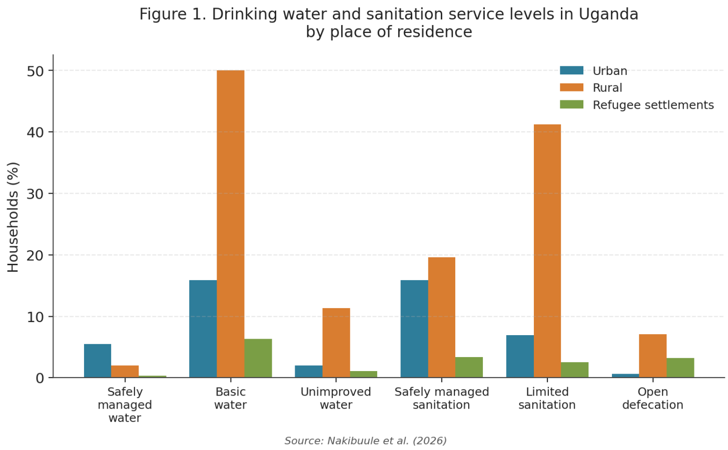

Figure 1: Drinking water and sanitation service levels in Uganda by place of residence

As Figure 1 shows, rural households fare consistently worse than urban households on nearly every indicator: half of rural households rely on merely basic drinking-water services against 15.9% of urban households, while rural open defecation, at 7.1%, is more than ten times the urban rate of 0.6%. These disparities confirm that the rural, peri-urban, and agricultural districts targeted by the integrated BSF–solar UV-C system in this review are precisely the populations least served by conventional water and sanitation infrastructure.

In Orom sub-county of Kitgum district, [30] found that the BSFs that were fed to the community can remove 96 percent of the coliform bacteria and comply with the national turbidity limits, borehole fed BSFs perform better than those fed from unprotected springs. The researchers at Kyambogo University established that sand depths of 453-580 mm are ideal to reduce the turbidity in surface water to the WHO recommended limit of 5 NTU to ensure effective downstream UV-C treatment. To tackle the chemical polluter aspect, [27] reported that arsenic, lead, manganese and cadmium were detected at high concentrations in the water sources in Kamuli district and suggested the use of locally available Ugandan zeolite from the Mbale district that has been proved to remove up to 98% of lead and 91% of arsenite. This method has been validated by [31] who found zeolite to be a potential cheap treatment to remove heavy metal concentrations that exceed the permissible limits set by the World Health Organization (WHO) in some surface water sources.

Besides, Uganda's environment fosters adoption. [10] noted that the average insolation is 4.5-5.5 kW/m² in most parts of the region, which offers sufficient solar power for off-grid rural settlements with UV-C systems. Furthermore, the strong growth of the schmutzdecke in biofilters caused by high organic loads from poultry and

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abattoir effluents makes the system more effective when dealing with these agricultural effluents than with effluents with low organic load like rainwater [32].

Community education and institutional support are vital to the success of technical deployment. Fieldwork in Nkokonjeru, Mukono District by [33], found that many BSF units were not working because of failure to properly maintain them, including failure to keep the schmutzdecke layer wet, and highlights the need for ongoing educational programs through local institutions, such as Makerere University and Busitema University. A system of community-based water supply management (CBMS) is already well established in Uganda whereby Water User Committees (WUCs) are charged with the maintenance of water facilities and collection of user fees [25]. For this to be a sustainable success, a deployment of the integrated BSF-solar UV-C system needs to be incorporated into this already highly successful WUC structure. But, this preparedness of institutions is not enough if the broader governance issues are not addressed. In Ugandan towns, water, sanitation and solid waste management services are often not integrated within existing planning methods which can make them context-conundrums that complicate service delivery, as documented by [34]. Moving from infrastructure provision to tackling these systemic barriers will require decisive action by national government and development partners to create a favourable policy environment for point of use technologies to be successful.

Open defecation remains an important, and frequently underappreciated, pathway of surface and shallow-groundwater contamination in rural Uganda. Even where the national open-defecation rate appears modest, the practice concentrates in exactly the low-income, poorly served districts where households also depend on unprotected wells, springs, and surface sources for drinking water, the same source waters targeted by the BSF-solar UV-C system reviewed here. Regional evidence corroborates this concentration risk: a pooled analysis across 33 sub-Saharan African countries found an open-defecation prevalence of 22.55%, disproportionately affecting the poorest and least-educated households [35], while baseline data from the Busoga WASH programme in eastern Uganda found that households relying on shared sanitation or open defecation faced a significantly elevated risk of waterborne diseases compared with households using private latrines [19]. This reinforces the case for a multi-barrier approach: even where upstream sanitation interventions reduce faecal contamination at source, downstream biofiltration and UV-C disinfection provide a critical second barrier against pathogens that continue to enter shallow water sources from inadequately managed excreta.

This is where ecological sanitation (ECOSAN) and the wider Ugandan WASH agenda intersect with the technology proposed in this review. ECOSAN systems, which safely contain and recycle human waste rather than allowing it to leach into groundwater, directly address the open-defecation and shared-sanitation pathways identified above. Uptake, however, remains constrained by non-technical barriers: in Soroti district, [36] found that willingness to adopt ecological sanitation toilets was hindered primarily by cultural taboos and could be improved through messaging delivered by trusted cultural leaders rather than through technical promotion alone, a finding that mirrors the community-education barriers already identified in the BSF literature above [33]. The integrated BSF-solar UV-C system is therefore best understood not as a stand-alone intervention but as one component of a broader multi-barrier WASH strategy for rural Uganda, sitting alongside ECOSAN-based excreta management, the Rural Water and Sanitation Program's institutional infrastructure, and VSLA-based community financing (discussed further in Section 5.3), in which source protection, safe excreta management, and household-level treatment together close the pathways through which contaminated water reaches rural consumers.

The economic argument for adoption is reinforced by the low operating costs of the system compared to other water sources such as bottled water or by the high costs of introducing centralized piped extensions, especially for community or cluster-based systems serving 10-20 households. The BSF-solar UV-C system provides a sustainable solution to meet SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) in Uganda using local materials and existing microfinance mechanisms like Village Savings and Loan Associations (VSLAs).

5.2 Technical Problems and Gaps in Research

Despite its considerable promise, there are a number of technical issues and research needs which will have to be addressed to facilitate the optimal implementation of the integrated BSF-solar UV-C system for Uganda.

Firstly, the challenge involves source-specific system optimisation. While the BSF-solar UV-C system has shown to be capable of treating the generic surface water and rainwater, a number of scientific investigations on the efficacy of the system in removing extreme levels of water pollution associated with poultry farm and abattoir runoff have not been rigorously conducted yet. Poultry and abattoir wastewater have been shown to have extremely high levels of turbidity, BOD and COD, heavy metals, and pathogen burden, including antibiotic-resistant pathogens linked to heavy metal co-selection in poultry feed [37] [38]. Hence, it should be ensured that the biofiltration stage is designed to effectively cope with such pollutant burden and provide water with a sufficiently low turbidity level for subsequent UV-C treatment.

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Secondly, there is an issue of optimisation of hydraulic design parameters in case of highly contaminated source water. The current CAWST v10 BSF system design has been mainly tested for use with moderately turbid surface water. High-strength poultry farm and abattoir wastewater would require faster replacement of sand and increased frequency of swirl-and-dump maintenance, thus temporarily deactivating the schmutzdecke filtration process, a failure mode already documented in Uganda [39]. Scientific study would help to define the optimal values of sand grading, sand depth and frequency of sand replacement to maintain the hydraulic loading rates below the recommended value of 400 $L/h/m^2$.

Thirdly, the maturation of the bio sand filter, which takes 10 to 40 days to form a stable schmutzdecke that ensures optimal performance, is another challenge associated with the use of the bio sand filter in areas where people need clean water immediately. Although this issue is inseparable from the technology, some research into ways of speeding up the formation of the schmutzdecke can be conducted (such as biofilm inoculation), so long as correct filter configuration is maintained throughout [39].

Fourthly, even though the solar-powered UV-C systems showed excellent results in laboratory settings, natural variability of water quality, seasonal variations in turbidity during the rainy season and limitations of battery capacity during prolonged cloudy weather may affect system performance, as Makerere University field study on solar disinfection in Kampala confirmed for turbidity and solar intensity [40]. It should be ensured that there is enough battery power in place and provisions for real-time turbidity monitoring to make sure that UV transmittance requirements are met.

There is also the question of removal of chemical contaminants, including such harmful substances as heavy metals (lead, cadmium, manganese) and residual antibiotics used in veterinary medicine. Even though BAC incorporation proved to be effective in reducing the levels of dissolved organic carbon in water, it has been less successful in reducing antibiotic and heavy metal pollution, which is typical for poultry farm and abattoir contaminated water [38]. Hence, further scientific research on the topic is needed.

Finally, the continuous involvement of the community, ownership, and maintenance are issues which have been known to be persistent problems for any household or community water treatment technology in a resource-poor environment. This was demonstrated by the Ugandan field work carried out by [33] at Nkokonjeru, where most filters were unused or misused not due to any technological fault but due to inadequate knowledge and follow-up support. This pattern recurs across WASH sector of Uganda: fewer than one in five Water User Committees assessed by [25] were fully functional, largely for want of reliable fee collection and caretaker training, while [41] found over half of surveyed households in Lwengo District had never contributed financially to upkeep, with payments typically made only after a breakdown rather than as preventive maintenance. Similar behavioural drivers govern sanitation uptake: [42] linked open-defecation-free status in Kabale district to household cleanliness habits rather than infrastructure alone, and [36] found willingness to adopt ecological sanitation in Soroti district hinged on awareness and perceived ease of use rather than cost. Community ownership, financial sustainability, and locally embedded technical support therefore deserve as much research attention as the engineering itself.

5.3 Current Adoption Status and Research Directions

The current uptake of the integrated BSF and Solar UV-C Disinfection in Uganda is largely at the awareness and pilot level, with the enabling environment for community scale uptake becoming increasingly positive [25] notes that if the water supply is to be reliable, it must be supported by well managed Water User Committees (WUCs) and Hand Pump Mechanics associations at the local level. However, a study conducted in Lwengo District by [41] and [43] showed that technical and financial challenges of community-managed systems are common in these systems with the majority of the challenges being lack of systematic training and dry schmutzdecke layer in Mukono District. [33] further observed that five out of eight filters failed to perform at a single school site in the municipality due to lack of user education ranging from improperly installed effluent tubes, to dry layers of schmutzdecke. Similarly, [30] reported that BSFs in Kitgum District achieved 96% efficiency in removing coliform bacteria and the results complied with the Uganda national turbidity limit of 10 NTU, with borehole water being more successful than the unprotected spring water.

These Uganda-specific results highlight the need for systematic community education and periodic testing/replacement, and the need to utilize solar UV-C as a second barrier to fill this performance gap. The technology includes the UV-C disinfection process which has not been tested in Uganda, but related research provides valuable design information. [27] of Kyambogo University also validated optimised sand bed depth specifications of 453-580 mm for slow sand filtration of Ugandan surface water that can meet/achieve the WHO turbidity limit of 5 NTU and can directly be applied to pre-treatment of dam water before UV-C disinfection; the same study also confirmed high level of arsenic, lead, manganese and cadmium in dam water in Kamuli district exceeding the limits set by WHO, and observed that natural zeolite from Mbale district can effectively reduce lead by up to 98% and arsenic by up to 91%, which can be used to enhance the slow sand filter media especially in situation where microbial and chemical contamination is present. The findings by [36] in Soroti

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district was significant as they identified that improved sanitation and water practices is often inhibited by cultural taboos, which suggests that messages from trusted cultural leaders can help increase the willingness to adopt improved practices. The study by [26] from field work in rural Uganda also reveals a substantial decrease in the pathogen load within houses equipped with community-built point-of-use filters, providing further evidence of the potential for the local implementation of point-of-use systems. The joint research between Ugandan institutions and researchers from other countries will speed up testing and evaluation of the integrated BSF, solar, UV-C system under Ugandan agricultural water source conditions, sand characteristics and practices.

Table 3 highlight the proposed technology within Uganda's existing household water treatment landscape, and Figure 2 compares the uptake of the main methods households currently use.

Table 2: Household water treatment practices relevant to Uganda

Indicator	Value	Source
Households practising any HWT (national)	49.6%	[44]
Households practising any HWT (rural)	49.7% (highest of 34 SSA countries surveyed)	[44]
Boiling	43.2%	[45], Kabale District
Chlorination / Water Guard	26.8%	[45], Kabale District
Plain sedimentation (settling)	23.0%	[45], Kabale District
Households regularly boiling or chlorinating	23–41%	[46], Busoga baseline survey

Source: Yitageasu et al, 2026

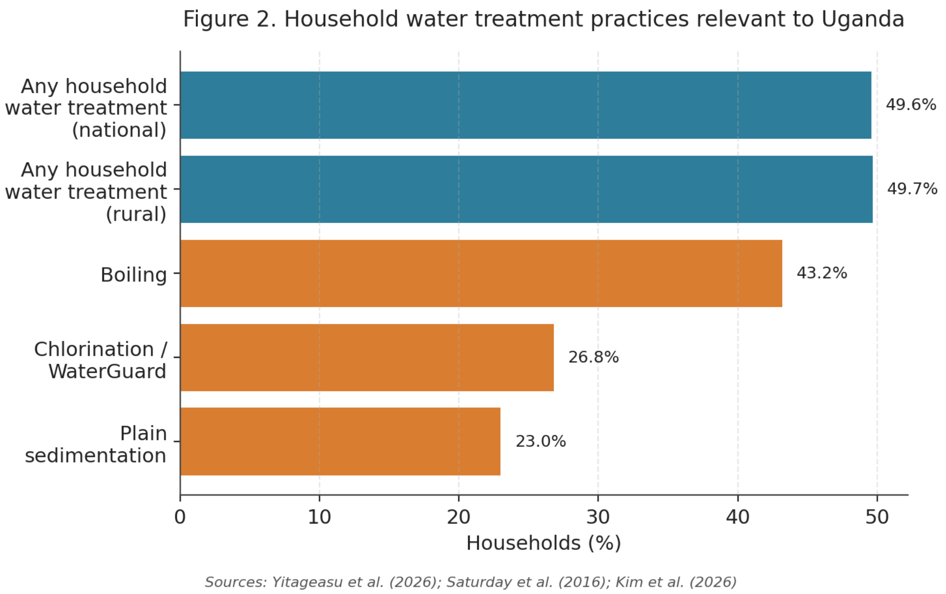

Figure 2: Household water treatment practices relevant to Uganda (**Sources**: Yitageasu et al., 2026; Saturday et al., 2016; Kim et al., 2026)

Uganda records the highest household water treatment uptake of the 34 sub-Saharan African countries examined in a recent geospatial analysis of Demographic and Health Survey data, at 49.6% nationally and 49.7% in rural areas specifically far above the sub-Saharan African average of 19.8% [44]. Boiling is the dominant household water treatment method both nationally and at district level. In studies such as that conducted in Kabale, 43.2% of households practised boiling, ahead of chlorination or Water Guard (26.8%) and plain sedimentation (23.0%) [45]. However, boiling depends on the availability of firewood or charcoal. Baseline data from the Busoga region found that only 23–41% of households treat their water regularly, with caregivers indicating fuel cost and time as the principal barriers despite widespread awareness that boiling is important [46]. Solar-powered UV-C disinfection sidesteps this fuel dependency entirely, offering a treatment pathway that does not compete with household cooking-fuel budgets, a practical advantage for the resource-constrained rural and peri-urban settings characterised in Table 1 and Figure 1, and a further argument, in addition to the technical reports above, for prioritising the integrated BSF-solar, UV-C system in the next research proposal.

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6.0 Conclusion

This review has established the technologic, economic and cultural viability of combining sand-based biofiltration with solar powered UV-C disinfection as a multi-barrier method for rural water treatment, especially for Uganda. The two technologies complement each other: biofiltration, which utilizes the schmutzdecke, mechanical straining, adsorption and biological predation to remove turbidity, organic load, and the vast majority of bacteria, is supplemented by the final barrier of UV-C disinfection, which is effective against viruses and resistant pathogens that biofiltration alone is not consistently and or capable of effectively removing.

Recent engineering innovations, like the CAWST Version 10 bio-sand filter, incorporating biologically activated carbon for organic and nitrogen removal, and the use of compact solar photovoltaic systems to power UV-C lamps, have boosted the performance of this combined system, to achieve under pilot conditions removal of bacteria >99.99%, turbidity <1 NTU, and a WHO recommended dose of 40 mJ/cm² using solar energy alone.

The case for deploying this technology in Uganda is based on both technical and social grounds. The results of this review are not surprising as nationally representative data shows that only 8.8% of Ugandan households have access to safe drinking water, while rural households (where half have only basic water coverage, and open defecation exceeds by over ten times that in urban areas) are exactly the ones this review has focused on (Table 1, Figure 1). The country's high solar insolation, availability of locally sourced sand and gravel and the favourable properties of the schmutzdecke promoted by agricultural effluents are also favourable to the integrated system, and the system's independence from firewood and charcoal is an advantage over the Ugandan families' most used system (boiling).

Concurrently, this review has identified technical and institutional gaps that need to be addressed prior to the scale up of the technology. There are still engineering challenges to overcome in the context of source-specific optimisation for high strength poultry and abattoir wastewater, hydraulic design for highly turbid source water, accelerating the maturation of schmutzdecke and treatment solutions for veterinary residues and heavy metals. Similarly, the apparent rate of filter failure, as found across the literature cited in this review, is not solely due to the filters, but to community training, failure to collect fees and support filters, and the need for as much research investment as the filter itself in these areas as well. The BSF-solar, UV-C system is not intended to be a standalone solution, but rather as a part of a comprehensive multi-barrier WASH solution, in conjunction with excreta management through ECOSAN, Water User Committees, and community financing through VSLA.

Research directions identified in this review that are desirable for future work include: field testing of the integrated system under conditions of contaminated poultry and abattoir-water sources in peri-urban districts in Uganda; source-specific characterization of contamination to inform locally applicable design parameters; life-cycle cost and willingness-to-pay studies; and community-based implementation research in collaboration with Ugandan universities, government ministries and NGOs. The integrated bio-sand filter and solar UV-C system is a decentralised, locally-resourced solution which supports SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 12 (Responsible Consumption and Production) directly for rural Uganda.

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References

[1] T. Ngai, J. Birkett, J. Mangal, R. McCandless, S. Murray, N. V. Anh, K. Guirguis, and C. Confidante, "Evolution of household BioSand filter design: A 20-year field study from Nicaragua, Bolivia, Cambodia, Nepal and Vietnam," in Water and Sanitation for the Base of the Pyramid. London, UK: IWA Publishing, 2014, pp. 159–184.

[2] A. O., Adeniyi, & M. O., Jimoh, Decontamination potential of ultraviolet type C radiation in water treatment systems: Targeting microbial inactivation. *Water*, *16*(19), Article 2725, 2024.

[3] O. O. Falowo and M. P. Otuaga, "A geo-environmental impact assessment of abattoir effluent discharge on groundwater quality in Igoba area of Ondo State, Nigeria," *Indonesian J. Earth Sci.*, vol. 2, no. 2, pp. 110–125, 2022.

[4] A. O. Ajanaku, O. O. Olusola, and B. A. Oyelami, "Effect of abattoir activities on the ground waters around Bodija and Akinyele abattoirs in Oyo State," *Int. J. Environ. Agric. Biotechnol.*, vol. 3, no. 3, pp. 1002–1010, May–Jun. 2018.

[5] M. Ng, S. Dalhatou, J. Wilson, P. Boniface, M. Temitope, P. H. Kamdem, H. Djelal, P. Nguyen-Tri, and A. Kane, "Characterization of slaughterhouse wastewater and development of treatment techniques: A review," *Processes*, vol. 10, no. 7, Art. no. 1300, 2022.
[6] X. Wu, S. Nawaz, Y. Li, and H. Zhang, "Environmental health hazards of untreated livestock wastewater: Potential risks and future perspectives," *Environ. Sci. Pollut. Res.*, vol. 31, no. 17, pp. 24745–24767, Mar. 2024.
[7] P. A. Adeoye, H. C. Man, M. A. Soom, A. M. Thamer, and A. C. Oluwakunmi, "Groundwater quality of shallow wells on Nigerian poultry farms," *Pol. J. Environ. Stud.*, vol. 23, no. 4, pp. 1079–1089, 2014.
[8] M. W. Jenkins, S. K. Tiwari, and J. Darby, "Bacterial, viral and turbidity removal by intermittent slow sand filtration for household use in developing countries: Experimental investigation and modeling," *Water Res.*, vol. 45, no. 18, pp. 6227–6239, Nov. 2011.
[9] O. O. Elemile, D. O. Raphael, D. O. Omole, E. O. Oloruntoba, E. O. Ajayi, and N. A. Ohwavborua, "Assessment of the impact of abattoir effluent on the quality of groundwater in a residential area of Omu-Aran, Nigeria," *Environ. Sci. Eur.*, vol. 31, no. 1, Art. no. 15, 2019.
[10] O. D. Basu, S. Dhawan, and K. Black, "Applications of biofiltration in drinking water treatment — a review," *J. Chem. Technol. Biotechnol.*, vol. 91, no. 3, pp. 585–595, 2016.
[11] I. Sriwijayasih, E. Novianarenti, T. E. Agustina, S. Nasir, R. Leonard, T. A. Rand, and I. L. Kusminah, "The treatment of Musi River water sample using slow sand filter and ultraviolet radiation (UV) with solar cell power sources," *J. Environ. Sci.*, vol. 8, no. 2, pp. 131–143, 2024.
[12] B. Primasari, S. Indah, R. Afrianita, and F. Rahmatesa, "Biosand filter for removal of organic pollutant from laboratory wastewater," *J. Phys.: Conf. Ser.*, vol. 1625, no. 1, Art. no. 012057, 2020.
[13] B. O. Orogbade, O. E. Ibiwoye, O. S. Olaniyan, M. A. Kareem, G. M. Amusan, and A. A. Olumide, "Design, construction and evaluation of performance of biosand filter for household water treatment," *FUOYE J. Innov. Sci. Technol.*, vol. 2, no. 1, pp. 33–41, 2022.
[14] J. K. Maiyo, S. Dasika, and C. T. Jafvert, "Slow sand filters for the 21st century: A review," *Int. J. Environ. Res. Public Health*, vol. 20, no. 2, Art. no. 1019, 2023.
[15] N. F. Gray, "Ultraviolet disinfection," in *Microbiology of Waterborne Diseases: Microbiological Aspects and Risks*, 2nd ed. London, UK: Elsevier, 2013, pp. 617–630.
[16] K. Chabi, J. Zeng, L. Guo, X. Li, C. Ye, and X. Yu, "Small-scale drinking water treatment unit of filtration and UV disinfection for remote area," *Water Sci. Technol.: Water Supply*, vol. 20, no. 6, pp. 2106–2118, 2020.
[17] A. B. Silva, N. M. Lima Filho, M. A. P. F. Palha, and S. M. Sarmento, "Kinetics of water disinfection using UV-C radiation," *Fuel*, vol. 110, pp. 114–123, 2013.
[18] A. T. Oyewale, T. A. Adesakin, O. Oyedeji, A. I. Aduwo, and M. K. Bakare, "Impact assessment of poultry discharge on the physico-chemical and microbiological water quality of Olosuru stream in Ikire, southwestern Nigeria," *J. Water Resource Protection*, vol. 10, no. 11, pp. 1061–1082, Nov. 2018.
[19] H. J. Kim, H. W. Yoon, M. A. Lee, Y. H. Kim, and C. J. Lee, "Impact of UV-C irradiation on bacterial disinfection in a drinking water purification system," *J. Microbiol. Biotechnol.*, vol. 33, no. 1, pp. 106–113, Jan. 2023.
[20] P. O. Nyangaresi, T. Rathnayake, and S. E. Beck, "Evaluation of disinfection efficacy of single UV-C, and UV-A followed by UV-C LED irradiation on Escherichia coli, B. spizizenii and MS2 bacteriophage in water," *Sci. Total Environ.*, vol. 859, Art. no. 160256, Feb. 2023.
[21] L. A. T. Garcia, F. L. Silva, B. L. S. Freitas, N. N. M. Fava, F. Reygadas, and L. P. Sabogal-Paz, "Efficiency of a multi-barrier household system for surface water treatment combining a household slow sand filter to a Mesita Azul® ultraviolet disinfection device," *J. Environ. Manage.*, vol. 321, Art. no. 115948, Nov. 2022.
[22] S. Mutemi, Z. Hoko, and H. Makurira, "Investigating feasibility of use of bio-sand filters for household water treatment in Epworth, Zimbabwe," *Phys. Chem. Earth*, vol. 117, Art. no. 102864, May 2020.
[23] C. Collin, *BioSand Filter Construction Manual.* Calgary, Canada: CAWST, 2009.
[24] *Guidelines for Drinking-Water Quality*, 4th ed., World Health Organization, Geneva, Switzerland, 2021.
[25] A. I. Rugumayo, "Rural water service delivery and innovations in Uganda," presented at the *39th WEDC International Conference*, Kumasi, Ghana, 2016.
[26] M. Benson, A. Noor, and J.-L. Moreau, "Clean water for all: Building filtration systems in rural Uganda," *Global Soc. Knowl. Rev.*, vol. 3, no. 7, pp. 11–22, Apr. 2025.
[27] C. Onyutha, E. Okello, R. Atukwase, P. Nduhukiire, M. Ecodu, and J. N. Kwiringira, "Improving household water treatment: Using zeolite to remove lead, fluoride and arsenic following optimized turbidity reduction in slow sand filtration," *Sustainable Environ. Res.*, vol. 34, no. 1, Art. no. 4, Mar. 2024.
[28] *Statistical Abstract 2024*, Uganda Bureau of Statistics, Kampala, Uganda, 2025.
[29] B. Nakibuule, H. M. Semakula, D. Nseka, H. Wasswa, C. Aboda, P. Nampereza, L. N. Namakula, and R. Ndejjo, "Categorization of household drinking water and sanitation service levels and associated determinants in Uganda," *Sci. Rep.*, vol. 16, Art. no. 6089, Jan. 2026.

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[30] J. D. Oyokarach and S. Tumusakye, "Evaluating the effectiveness of the existing biosand filters to remove pathogens and suspended particles in water and provide safe water, Orom Sub-County (Kitgum District)," Final year project report, Sch. Eng. Appl. Sci., Kampala Int. Univ., 2019.

[31] P. R. Biira, "Water supply system design and environmental monitoring for the Namatala Water Treatment Plant project," Professional Report, 2026.

[32] M. G. de Melo Neto, B. L. S. Freitas, N. N. M. Fava, and L. P. Sabogal-Paz, "Rainwater treatment system efficiency: Household slow sand filter combined with UVC lamp disinfection," *J. Water Process Eng.*, vol. 58, Art. no. 104785, Feb. 2024.

[33] M. E. Spowart, "Educational concerns of implementing biosand water filters in rural Uganda," M.S. thesis, Dominican Univ. of California, San Rafael, CA, USA, 2012.

[34] R. Sakaya, C. Lüthi, A. S. Narayan, J. Fritzsche, A. Y. Katukiza, and C. B. Niwagaba, "The context-conundrum: Why existing planning methodologies fail in the integration of water, sanitation and solid waste management services in small towns," *Environ. Sci.: Adv.*, vol. 5, no. 6, pp. 145–159, Jun. 2026.

[35] D. G. Belay, M. H. Asratie, F. M. Aragaw, N. T. Tsega, M. Endalew, and M. Gashaw, "Open defecation practice and its determinants among households in sub-Saharan Africa: Pooled prevalence and multilevel analysis of 33 sub-Saharan Africa countries demographic and health survey," *Trop. Med. Health*, vol. 50, Art. no. 20, Mar. 2022.

[36] B. O. Ikiring, D. Okia, C. Okolimong, J. P. Alunyo, R. Katuramu, A. T. Khainza, D. Mukunya, J. K. B. Matovu, D. Musoke, P. Olupot-Olupot, and B. Wanume, "Factors associated with willingness to use ecological sanitation toilets in Katine sub county Soroti district Uganda: a cross-sectional study," *Sci. Rep.*, vol. 15, Art. no. 36403, Oct. 2025.

[37] D. Nimusiima, D. Byamugisha, T. Omara, and E. Ntambi, "Physicochemical and microbial quality of water from the Ugandan stretch of the Kagera transboundary river," *Limnol. Rev.*, vol. 23, no. 3, pp. 157–176, Nov. 2023.

[38] T. Ssemakadde, N. Pauline Petra, J. C. Busingye, J. Bazira, and K. Taseera, "Prevalence and antimicrobial resistance of Salmonella and pathogenic E. coli in broiler farms, Wakiso district, Uganda," *PLoS ONE*, vol. 20, no. 7, Art. no. e0309599, Jul. 2025.

[39] P. Dandadzi and N. K. Kothurkar, "Assessing the sustainability of biosand filters: Unveiling interlinkages and leveraging factors for effective implementation," *Environ. Sustain. Indicators*, vol. 20, Art. no. 100311, Dec. 2023.

[40] K. Okurut, E. Wozei, R. Kulabako, L. Nabasirye, and J. Kinobe, "Calibrating an optimal condition model for solar water disinfection in peri-urban household water treatment in Kampala, Uganda," *J. Water Health*, vol. 11, no. 1, pp. 98–109, Mar. 2013.

[41] D. Etongo, G. H. Fagan, C. Kabonesa, and R. B. Asaba, "Community-managed water supply systems in rural Uganda: The role of participation and capacity development," *Water*, vol. 10, no. 9, Art. no. 1271, Sept. 2018.

[42] M. Ntaro, J. B. Isunju, E. Mulogo, and J. C. Ssempebwa, "Open defecation free status and its determinants in rural Uganda: a cross-sectional survey," *BMC Public Health*, vol. 25, no. 1, Art. no. 1974, Sept. 2025.

[43] R. B. Asaba, "Gender and representation in local water governance in rural Uganda," *Int. J. Agric. Resour. Gov. Ecol.*, vol. 11, no. 3–4, pp. 247–259, Dec. 2015.

[44] G. Yitageasu, E. A. Alemu, A. K. Gebrehana, A. A. Asnake, and L. Demoze, "Geospatial analysis and prevalence estimation of household drinking water treatment in sub-Saharan African countries: Insights from recent demographic and health surveys," *J. Egypt. Public Health Assoc.*, vol. 101, no. 1, Art. no. 10, Mar. 2026.

[45] A. Saturday, G. L. Makokha, and A. Macharia, "Performance of household water treatment methods for microbial removal under household conditions in Kabale District, Uganda," *J. Environ. Health Sci.*, vol. 2, no. 2, pp. 1–9, 2016.

[46] D. Kim, J. S. Hoon, G. Ssekitoleko, L. Ruvwa, M. Kyangwa, D. Atwesigye, P. D. Kavuma, B. Ssemwogerere, S. Achiro, A. Muganda, B. D. Tatumwa, and K. Mwebaza Muluya, "Waterborne diseases burden, determinants and health system gaps in Eastern Uganda: A mixed-methods baseline study in the Busoga region," *Front. Public Health*, vol. 14, Art. no. 1808626, May 2026.

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