MadiDrop®

Scaling Silver Ionization for Safe School Water in India

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Effectiveness of the upscaled use of a silver–ceramic (silver ionization) technology to disinfect drinking water in tanks at schools in rural India

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ABSTRACT

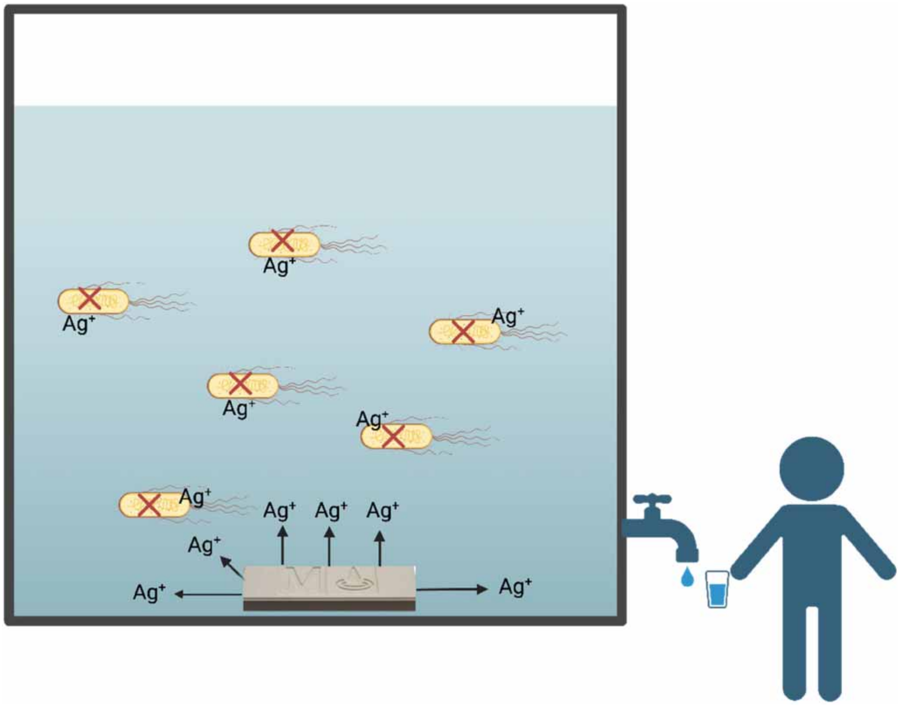
In many low- and middle-income countries, school children consume untreated water that has been pumped into storage tanks. The water is often of poor quality and consumption can cause gastrointestinal illnesses resulting in missed school days, growth stunting, and cognitive impairment. This study deployed a silver–ceramic technology (MadiDrop) to disinfect drinking water in school storage tanks. While silver ionization is effective at the household scale, relatively little research has been conducted on its effectiveness at the community scale. To address this gap, we assessed disinfection via MadiDrop at three schools that serve vulnerable populations in rural India. Tank inflow and treated outflow samples were tested for total coliforms (TCs) and *Escherichia coli* (EC). TC was significantly reduced overall and in two of three intervention tanks. Compared to the baseline, reductions in TC were significant in all three tanks and overall, while EC reductions were significant overall and in two of three tanks. TC reduction was negatively correlated with silver concentration and tank residence time, and silver concentrations were maintained below the drinking water quality guideline. While the intervention could be considered successful, several barriers and caveats are provided as are study limitations and areas for future research.

Key words: bacterial removal, drinking water disinfection, India, MadiDrop, silver ionization, water tanks

HIGHLIGHTS

- Novel use of MadiDrop (silver ionization) to disinfect drinking water in tanks at schools in India.
- Reduced total coliforms and *Escherichia coli*, and silver concentrations were maintained below the guideline.
- Total coliform concentrations were negatively correlated with tank residence time and silver concentration.
- Recommendations for deploying silver ionization at the community scale and in low-resource settings are provided.

GRAPHICAL ABSTRACT



INTRODUCTION

In many low- and middle-income countries, schools serve untreated drinking water that has been pumped into storage tanks. Water flows from the tanks (by gravity) to taps for consumption by children. Because the water is often of poor quality, pathogens may be present that cause gastrointestinal infections. This can lead to missed school days, stunted growth, cognitive impairment, and in extreme cases, death (Bain *et al.* 2014; McMichael 2019). While water can be dosed with chlorine, some communities lack the capacity to manage such systems as they require dosing appropriate masses of $Ca(OCl)_2$ on a daily basis coupled with managing purchasing and supply processes (Harris 2005). Furthermore, chlorination often faces resistance because it causes a noticeable change in taste and aesthetics (Crider *et al.* 2018; Spackman & Burlingame 2018), not to mention the possible generation of hazardous disinfection byproducts (Kali *et al.* 2021).

This study deployed an emerging silver–ceramic technology called MadiDrop to disinfect drinking water in storage tanks at schools in rural India. MadiDrop is a 52-g porous ceramic tablet embedded with micro-patches of metallic silver that can disinfect 10–20-L batches of water per day for up to 1 year. The tablet is placed in a water storage container where silver ions are passively released into the water. Users fill the containers at night, and in the morning the water is biologically safe to drink (Ehdaie *et al.* 2017; Hill *et al.* 2020). The advantages of MadiDrop are that it is low-cost (0.2 US cents/L), simple to use, requires no additional infrastructure (simply a water container), and produces water that is aesthetically acceptable since there is no change in taste, or odor, or other physical characteristics (Pacey 1977; Bhardwaj *et al.* 2021).

Silver ionization, typically through ceramic silver-impregnated pot filters, is effective at the household scale (e.g., 10–20 L batches) (Gupta *et al.* 2018; Rivera-Sánchez *et al.* 2020). However, very little laboratory or field research has been conducted on its effectiveness at larger scales (e.g., 100–500 L). To address the research gap, this pilot study implemented silver ionization treatment with MadiDrop tablets at the community scale by engaging schools that serve drinking water to marginalized, at-risk populations via storage tanks that are several hundred liters in volume.

The objective of this study is to assess the effectiveness of MadiDrop at removing total coliforms (TCs) and *Escherichia coli* (EC) from drinking water at the community scale (i.e., tanks at schools) while maintaining effluent silver concentration levels below the World Health Organization (WHO) drinking water quality guideline of 100 μg/L (WHO 2018). Additionally, this study seeks to identify various barriers and caveats that affect the successful use of MadiDrop and other silver ionization treatment methods at the community scale.

METHODOLOGY

Study area and storage tanks

This study deployed MadiDrop, an emerging silver ionization point-of-use (PoU) water treatment method, at three schools in rural Gurugram District, Haryana, India (Figures 1 and 2). The schools are located in one of the most socioeconomically disadvantaged regions of India that simultaneously struggles with chronic water scarcity (Tanwar & Hooda 2018; Goel *et al.* 2020). The schools serve a large percentage of population identified as 'Scheduled Caste,' 'Other Backwards Class,' and *antyodaya* (best translated as 'welfare of people at the bottom of the pyramid'). These official terms mean that the Government of India has denoted the communities as 'poorest of the poor' and they are therefore granted formal Reservations (i.e., a system

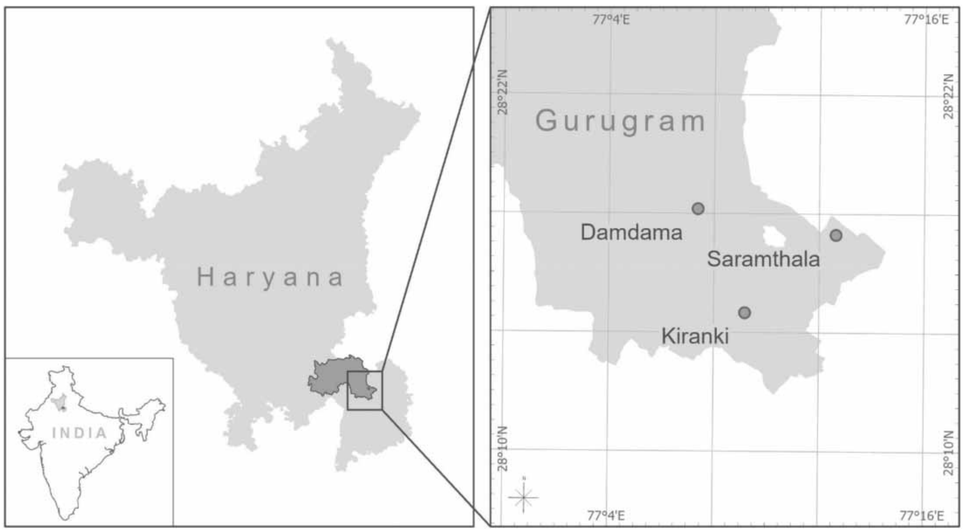


Figure 1 | Locations of the three schools in rural Gurugram District, located in the state of Haryana, India.

Figure 2 | Examples of rainwater (left) and groundwater (right) supplied drinking water tanks at schools in the study area.

of affirmative action that sets quotas for historically disadvantaged groups or 'socially and educationally backwards citizens' in education admissions, employment, government programs, and political seats).

The three schools are located in the rural settlements of Damdama, Kiranki, and Saramthala with total school populations of approximately 165, 205, and 170 students and staff, respectively. The schools exhibit a variety of tank volumes, dimensions, materials, and drinking water sources, as shown in Table 1. This diversity in tanks and source waters – including one with biosand filtration – provided valuable insight into the performance of the MadiDrop technology. Furthermore, variations in water usage rates and the presence of weekends and holidays (when the MadiDrops had extended contact time) facilitated a realistic understanding of managing MadiDrop vis-à-vis real-world practicalities. All research and data collection activities were performed according to approved institutional ethical standards (Virginia Tech IRB #22-371) as well as an additional layer of standards deemed important by the schools and research team.

Materials and methods

Prior to disinfection, a Monte Carlo simulation was developed in R to inform MadiDrop deployment for each tank (Figure 3). The model considered variables such as tank volume and dimension, outflow tap height, tank filling time(s), hours of school operation, and estimated daily water usage rates based on total school population and other demographic and contextual factors. Weekends and randomized series of days were also incorporated to account for water sitting in the tanks (i.e., in contact with the MadiDrops) for extended periods of time. Silver ion release rates from the MadiDrop tablets were determined via laboratory experiments at the University of Virginia to help maintain silver concentrations below the 100 μg/L drinking water quality guideline. Furthermore, the model allowed for the bottom and vertical positioning of MadiDrops in the

Table 1 | Descriptions of the drinking water storage tanks

School	Water source	Tank size (L)	Tank dimension (mm)	Tank material	Treatment
Damdama	Borehole	234	Dia. – 720 H – 575	PVC	None
Kiranki	Rainwater	234	Dia. – 720 H – 575	PVC	None
Saramthala	Rainwater	517	L – 838 W – 838 H – 736	Brick masonry	Biosand filtration before MadiDrop

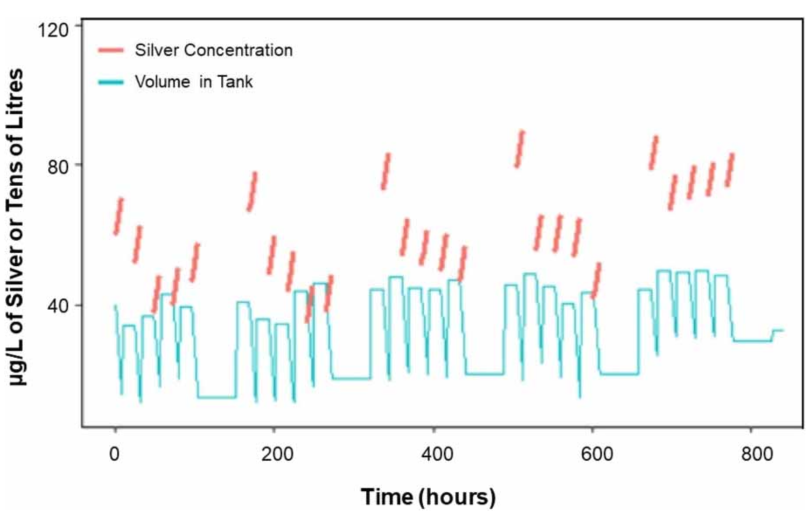


Figure 3 | A model iteration that seeks to generate silver concentrations below the 100 μg/L drinking water quality guideline during the hours of school operation (when water is consumed) while considering tank filling time(s) and various temporal and physical parameters. Red lines visualize simulated silver concentrations during actual times of water consumption, which range from roughly 35 to 95 μg/L.

tanks. Vertical positioning controls how many MadiDrops are in contact with the drinking water as the level in the tank rises and falls from refilling and usage. This allows for greater control of silver concentration levels compared to all tablets being positioned on the bottom of the tank (in which case water would always be in contact with all of the tablets, thereby increasing the risk for silver concentrations above the guideline).

Next, to establish a baseline for each tank, triplicate influent and effluent water samples were collected and tested from each tank over the course of one week according to the methods described below. Baseline tests were followed by the insertion of the appropriate number of MadiDrops along with a Heron dipperLog vented pressure transducer. The pressure transducer logged tank inflows and outflows at continuous 15-min intervals to enable the monitoring of water usage and tank filling times as well as to inform water treatment, water quality testing, and refinements to the computer model. The tanks were then emptied and refilled every 1–3 days to mimic actual water usage along with weekends, holidays, and other anticipated irregularities.

After introduction of the MadiDrop, inflow and treated outflow samples from each tank were collected three times per week for 5 weeks from December 2022 to January 2023. Samples were collected using sterile Nasco Whirl-Pak bags and stored on ice between 2 and 8 °C according to Standard Methods (Lipps *et al.* 2023). Samples were tested for TC and EC concentrations at the S M Sehgal Foundation water quality laboratory within 5 hours of collection. Duplicate samples from each tank (two inflow and two treated outflow samples) were diluted with deionized water to contain a total of 1, 5, or 10 mL of inflow and/or treated outflow water guided by baseline data collection. The membrane filtration method utilizing MilliporeSigma m-Coliblue24 broth culture media was used to determine colony forming units (cfu) per 100 mL. Samples were incubated for 24 h at 35 °C. All units were counted as TC and only dark units were counted as EC. A control test of deionized water was also conducted each time.

Silver concentrations of treated samples were measured at the TERI School of Advanced Studies using a Hach DR 5000 UV–vis spectrophotometer. A standard curve was generated using the Hach silver standard solution and tests were performed using the Hach silver reagent and sodium thiosulfate pillows according to the colorimetric method. Results were confirmed by remeasuring acidified samples using an Agilent 7900 inductively coupled plasma mass spectrometer (ICP-MS) at the University of Virginia. A Vernier turbidity sensor was used to determine nephelometric turbidity units (NTU) in both inflow and treated outflow samples. After the intervention, MadiDrops were removed from the tanks, the tanks were emptied, and a second pair of three inflow and three outflow baseline tests were conducted for each tank over the course of 1 week.

Analyses

Results were analyzed using both descriptive and inferential statistics. Descriptive statistics such as standard deviation (SD) and percent reduction in TC and EC concentrations were computed in Microsoft Excel for tank inflow, treated outflow, and baseline samples. For inferential statistics, the normality of the data was found in R Studio using a Shapiro–Wilk test. To compare TC and EC concentrations between inflow samples and outflow samples treated with MadiDrop, a one-tailed Wilcoxon rank-sum test (Mann–Whitney U test) was performed in JMP Pro 16.0.0 for each tank and for the overall set of three tanks. The p-values were calculated using the chi-squared approximation method. The strength and direction of relationships between percent reduction in TC concentrations and tank residence time, silver concentration, and turbidity were assessed for each tank and the overall set of three tanks using Spearman's rank correlation coefficient (Spearman's rho) in JMP Pro. A coefficient closer to -1 suggests a more pronounced negative correlation, meaning a stronger tendency for the variables (e.g., TC and silver concentration) to move in opposite directions.

RESULTS

Statistical analyses determined that TC concentrations were significantly different ($p \leq 0.05$) – in this case, reduced – when comparing outflow samples treated with MadiDrop to inflow samples in two of three intervention tanks and among the overall set of three tanks (Table 2). Additionally, TC concentrations were significantly different (i.e., reduced) when comparing treated outflow samples to baseline outflow samples across all three tanks and as an overall set. For EC, concentrations were reduced in all treated outflow samples (relative to inflow) overall and in all tanks with EC detected, although none of the comparisons were significant. However, when comparing treated outflow samples to baseline outflow samples, EC reduction occurred across the board and was significant overall and in two of three intervention tanks.

In terms of actual reductions in bacteria, TC concentrations were reduced across all three intervention tanks and by >63% overall, while EC concentrations were reduced across two of two tanks and by >70% overall. These descriptive results are

Table 2 | | Statistical comparisons (*p*-values) of bacteria concentrations in treated outflow vs. inflow and baseline outflow

	Damdama	Kiranki	Saramthala[a]	Overall
TC outflow vs. TC inflow	**0.0025***	< **0.0001****	0.1865	< **0.0001****
TC outflow vs. TC baseline	**0.0008****	**0.0009****	**0.0004****	< **0.0001****
EC outflow vs. EC inflow	0.9682	0.1476	–	0.6344
EC outflow vs. EC baseline	**0.0012***	**0.0145***	0.1025	**0.0183***

Notes: Based on TC and EC cfu per 100 mL. No EC detected in Saramthala inflow and outflow.
[a]Saramthala water undergoes biosand filtration prior to intervention treatment.
*Significantly different at 95%.
**Significantly different at 99%.

summarized in Table 3 and visualized in Figures 4 and 5 as well as Figures 6 and 7. Moreover, bacterial removal via silver ionization has been shown to be associated with silver concentration level, contact time with the medium that is releasing silver (e.g., MadiDrop), and turbidity (Zhao & Stevens 1998; Harris *et al.* 2023). In this case, overall, there was a significant negative correlation ($p \leq 0.05$) between TC concentrations in inflow samples compared to treated outflow samples when

Table 3 | Descriptive comparisons of bacteria reductions in treated outflow vs. inflow

	Damdama	Kiranki	Saramthala[a]	Overall
TC reduction (outflow vs. inflow)	75.9%	77.8%	34.7%	63.4%
Average TC: inflow, outflow	240, 68	703, 52	374, 35	544, 87
Median TC: inflow, outflow	235, 8	655, 84	27, 20	360, 34
TC Standard Dev.: inflow, outflow	124.50, 132.84	176.58, 179.65	893.67, 29.01	690.03, 147.98
EC reduction (outflow vs. inflow)	99.9%	68.1%	–	70.3%
Average EC: inflow, outflow	6, 0.2	117, 36	–	43, 13
Median EC: inflow, outflow	0, 0	55, 35	–	0, 0
EC Standard Dev.: inflow, outflow	16.67, 0.67	133.35, 37.54	–	121.12, 27.59

Notes: TC and EC cfu per 100 mL. No EC detected in Saramthala inflow and outflow.
[a]Saramthala water undergoes biosand filtration prior to intervention treatment.

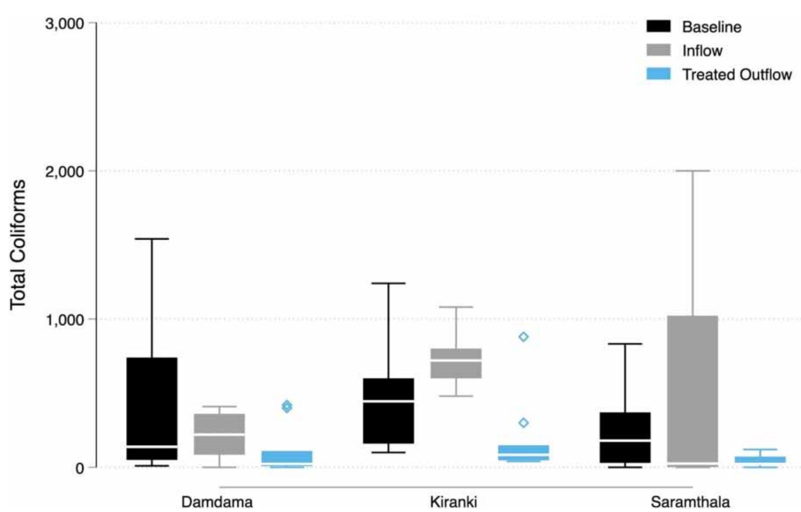


Figure 4 | Box plots of TC per 100 mL in baseline, inflow, and treated outflow samples. (*Note*: One outlier removed each from Kiranki baseline (7,200), Kiranki inflow (4,360), and Saramthala inflow (2,800) for purposes of visualization.)

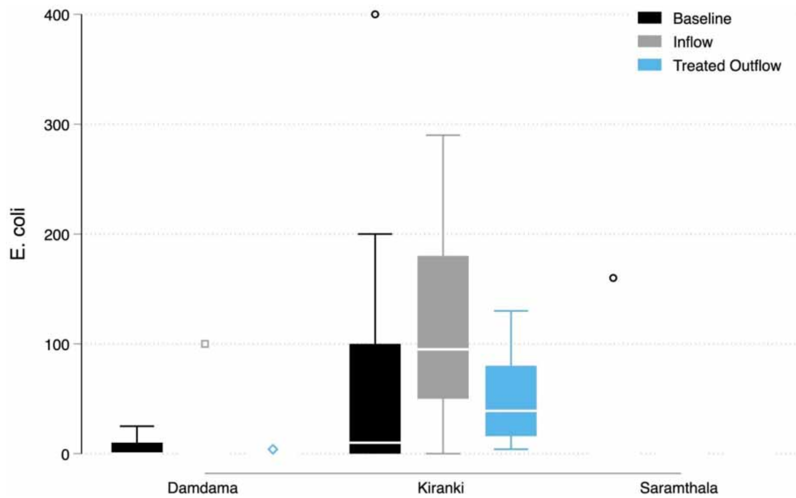


Figure 5 | Box plots of EC per 100 mL in baseline, inflow, and treated outflow samples. (*Notes*: Two outliers were removed from Kiranki baseline (3,360 and 3,200) and one was removed from Kiranki inflow (780) for purposes of visualization; no EC was detected in Saramthala inflow and treated outflow samples.)

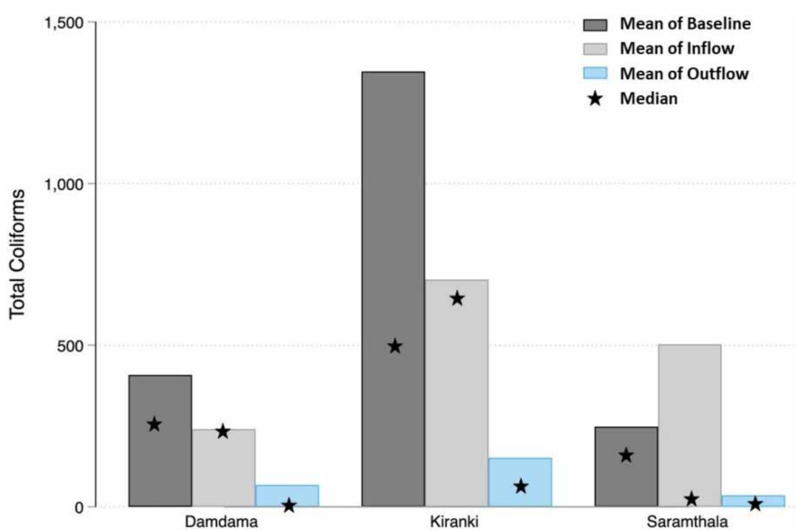


Figure 6 | Bar charts of mean and median TC per 100 mL in baseline, inflow, and treated outflow samples.

considering both tank residence time (i.e., contact time with MadiDrop) and silver concentration (Table 4). No significant relationships were identified between TC concentrations and turbidity. Silver concentrations were consistently maintained below the drinking water guideline (no samples exceeded 100 μg/L). Descriptive summary data on silver concentrations and turbidity are provided in Table 5.

DISCUSSION

This study sought to evaluate the effectiveness of MadiDrop at removing TC and EC from drinking water tanks at three schools in rural India while maintaining effluent silver concentrations below the drinking water quality guideline of 100 μg/L. Additionally, this study aimed to identify barriers and caveats that affect the successful deployment of MadiDrop and similar water treatment methods at the community scale. This section dissects these topics while also providing study limitations and future research directions.

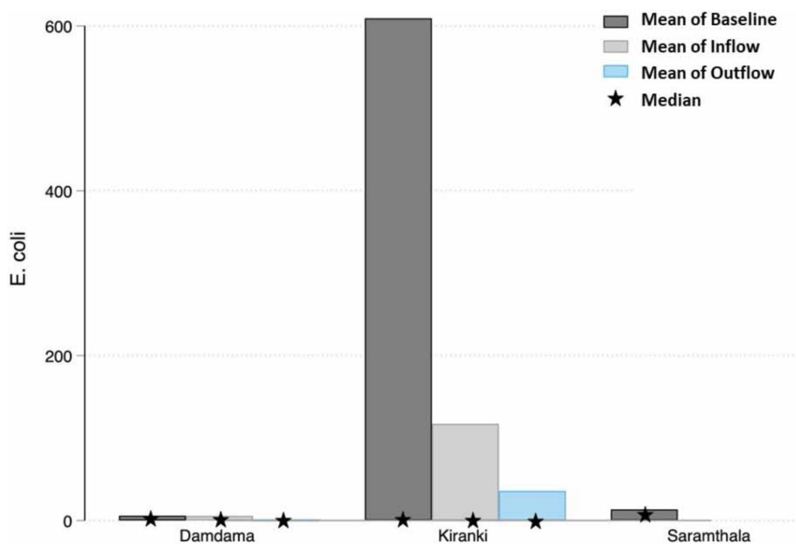


Figure 7 | Bar charts of mean and median EC per 100 mL in baseline, inflow, and treated outflow samples. (*Note*: No EC detected in Saramthala inflow and treated outflow samples.)

Table 4 | Statistical relationships (*p*-values and coefficients) between bacteria concentrations in treated outflow and environmental conditions

	Damdama	Kiranki	Saramthala[a]	Overall
TC and tank residence time	0.0710 (−0.6667)	**0.0288*** (**−0.7197**)	0.4927 (– 0.2857)	**0.0274*** (**−0.4409**)
TC and silver concentration	**0.0446*** (**−0.7186**)	0.3914 (−0.3264)	0.2070 (– 0.500)	**0.0116*** (**−0.4963**)
TC and turbidity	–	0.2013 (−0.4704)	0.2894 (0.4286)	0.6651 (– 0.0911)

Notes: Based on TC cfu per 100 mL. Unable to determine/no monotonic relationship between Damdama TC and turbidity.
[a]Saramthala water undergoes biosand filtration prior to intervention treatment.
*Significantly correlated at 95% (coefficient).

Table 5 | Silver concentrations and turbidity in treated outflow

	Damdama	Kiranki	Saramthala[a]	Overall
Silver concentration (mean, median)	9.6, 11.3	11.3, 12.5	11.4, 12.1	10.8, 12.1
Silver concentration (range, SD)	4.0–13.0, 3.21	3.5–14.9, 3.62	2.5–14.4, 3.49	2.5–14.9, 3.42
Turbidity (mean, median)	5.7, 4.1	3.9, 3	4.1, 5.7	4.6, 3.6
Turbidity (range, SD)	1.2–9.1, 2.89	0.7–7.6, 2.72	1–10.9, 3.23	0.7–10.9, 2.96

Notes: Silver concentrations measured in μg/L, turbidity measured in NTU. WHO drinking water guideline is <100 μg/L.
[a]Saramthala water undergoes biosand filtration prior to intervention treatment.

Effectiveness of disinfection

Results determined that TC and EC concentrations were reduced in every tank and when considering all samples as an overall set (Table 3). TC was significantly reduced in two of three tanks and overall, and reductions in TC and EC were significant compared to baseline data in seven of eight comparisons (Table 2). Although some EC comparisons were insignificant, we contend a governing factor may be that EC concentrations were not highly elevated to begin with and therefore there was not a large amount to remove. (Not to mention that silver concentrations remained at a relatively low level, which will be discussed later.) This is attested to by the tank at Saramthala, which had no EC to remove since the influent undergoes biosand filtration prior to intervention disinfection. Despite cases of insignificant EC reduction, Table 3 and the plots in Figures 5 and 7 demonstrate that EC reduction still eclipsed 70% overall and that reduction occurred across all tanks, especially in the tank at Kiranki that exhibited the highest EC concentrations. In fact, because EC concentrations were consistently quite low, outliers from untreated samples at Kiranki were manually removed from the box and whisker plots in Figure 5 solely to better visualize the data. If the outliers were included, the plots became so compressed that there was virtually nothing to discern. Note that including the outliers in Figure 5 – which was done in all statistical analyses and descriptive statistics – would have actually made EC reduction look *greater* in the plots (i.e., this is not a misrepresentation or exaggeration of data). However, doing so would have compromised visualization of the plots for Kiranki as well as Damdama to a lesser extent.

Overall, TC concentrations were negatively correlated with tank residence time (i.e., contact time with MadiDrops) and effluent silver concentration (Table 4). These correlations are intuitive as it was hypothesized that longer durations of contact time with the silver–ceramic technology and higher silver concentrations would positively affect disinfection. While it was also hypothesized that turbidity may negatively impact disinfection (i.e., greater turbidity would lead to lower TC and EC removal), the statistical tests were insignificant. This result contradicts Zhao & Stevens (1998) and Harris *et al.* (2023) but is in agreement with those of Ehdaie *et al.*'s (2017) fieldwork in South Africa. We contend that this result is (partly) due to the source waters (rainwater and groundwater) not being very turbid. Considering all tanks, the mean and median were 4.6 and 3.6 NTUs, respectively. While these NTUs are not ideal, we contend that they are not exceedingly elevated and therefore turbidity might not have been great enough to significantly impede disinfection. That being said, turbidity is an impediment to disinfection, and turbidity has been shown to reduce the effectiveness of silver ionization. This is especially a factor when treating surface water, which is generally more turbid compared to rainwater and groundwater and also tends to contain more biological contaminants. Thus, the source water should be tested before deploying MadiDrop (or any disinfection technology), with high NTUs signifying that more tablets or greater contact time may be required.

An extremely important result was sustaining silver concentrations below the WHO drinking water quality guideline in every treated outflow sample. The ability to do so was aided by the model that was developed. However, although the model called for 29.6, 31.5, and 50.2 MadiDrops in the tanks at Damdama, Kiranki, and Saramthala, respectively, we elected to insert only 26, 26, and 31 tablets based on public health concerns and water consumption dynamics observed during the baseline. Since this was a pilot study with schools that serve vulnerable populations, we consciously chose to deploy fewer MadiDrops out of an abundance of caution. In particular, we wanted the water to be safe if a school happened to leave water in the tank over the weekend or for an extended period of time. Second, fewer tablets were deployed based on actual water usage observed during baseline data collection (which was less than was estimated in the model). As a result, overall silver concentrations averaged only 10.8 μg/L with a median of 12.1 μg/L (Table 5). This leads to three contentions: (1) the model appears to be practical; (2) model results are roughly in line with estimated calculations of one MadiDrop tablet per 10–20 L (i.e., the intended volume to be treated by a single tablet); and (3) TC and EC were still reduced in every case (often significantly) with considerable room to increase silver concentrations to enhance disinfection. In fact, maintaining 70–90 μg/L would be ideal, meaning that silver concentrations could be increased many times over. Additionally, the cost per liter treated is only US $0.0021 while it is estimated (based on current market prices) that chlorine tablets like Aquatabs cost $0.02 per liter and P&G Purifier sachets cost $0.075 per liter, rendering MadiDrop relatively cost-effective compared to other common PoU disinfection methods.

Barriers and caveats

While this pilot intervention could be considered successful, several barriers emerged. First, users must be able to deploy and manage the disinfection technology appropriately. This requires basic data (e.g., tank volume, dimensions, and estimates of inflow–outflow per day) in order to simulate how many MadiDrops are needed. In turn, this requires guidance from an expert or access to the model and the ability to use it. Alternatively, a simple 'back-of-the-envelope' calculation that estimates how many MadiDrops are needed based on tank volume and general/assumed usage would be valuable. Next, the ability to measure silver concentrations was identified as a barrier. Silver standard solution, reagents, and other consumables needed to measure silver concentrations were unavailable in India, and therefore these materials had to be brought into the country. This presents a significant barrier as monitoring silver concentrations requires access to a laboratory, equipment (e.g., spectrophotometer), and associated consumables that may be unavailable or cost-prohibitive in low-resource contexts.

Several practical barriers also arose. First, some of the tank inflows were difficult to access and it can be difficult to gain access to the inside of tanks to add and position the MadiDrop tablets. Next, tank management is of foremost concern. Water should reside in the tank in contact with the tablets overnight, and the tank should be regularly emptied (if not fully or mostly used) and refilled to safely manage silver concentrations. This demands a dependable, trustworthy staff who can manage the tank in cases of water sitting over weekends, holidays, school closures, or other circumstances. For this reason, and as mentioned earlier, we elected to deploy fewer MadiDrops than the model stipulated to err on the side of caution. Vertically positioning tablets inside the tank can also be difficult. To accomplish this, we hung fishing lines into the tanks with tablets tied on at the simulated heights. Finally, users of this technology must still remember to implement other water, sanitation, and hygiene (WASH) best practices. While MadiDrop has been shown to improve water quality, maintaining a clean tank, sludge removal, and other safe storage and serving activities should still be practiced to promote water quality.

In terms of caveats, an interesting yet expected finding was that the tanks themselves presented TC and EC hazards that were difficult to account for. We sought to understand the tank ecosystems, as explored by Salehi (2022) in the case of storage tanks and Juran & MacDonald (2014) in the case of post-treatment drinking water storage, with the hypothesis that TC and EC already exist in the tanks and thus water entering the tanks – without any treatment – would be better quality (at best the same) than after it flows from the tanks. As expected, the tank ecosystems – level of cleanliness, presence of biofilm, sludge, and other residues and constituents, and instances of low dissolved oxygen in times of prolonged storage – negatively affected the initial quality of inflow water. For example, baseline tests of inflow and untreated outflow samples established that outflow samples from the tank at Kiranki averaged an increase of 993 TC and 1,182 EC compared to inflow samples. At Damdama, baseline samples averaged an increase of 22 TC and 3 EC after flowing through the tank, while outflow samples from Saramthala averaged an increase of 40 TC (no EC detected in inflow or outflow). These data demonstrate and further stress the criticality of maintaining a clean tank, regularly removing biofilm and sludge, and conducting other household water treatment and safe storage (HWTS) activities to promote and maintain water quality. Regarding the use of MadiDrop in the tanks, we therefore contend that the tablets were removing TC and EC that were present in the inflow *as well as* TC and EC that were already present in the tanks. This means that MadiDrop not only produced effluent with fewer TC and EC than were present in the source water, but it did so while also eliminating additional, unaccounted for TC and EC that were part of the tank ecologies and premise plumbing.

Another caveat that should not be overlooked is the residual disinfection capacity provided by the silver ions as well as MadiDrop's ability to reduce other health hazards such as *Cryptosporidium parvum*, *Giardia lamblia*, *Adenovirus*, and mosquito larvae (Turner 2023). Thus, while this pilot study only considered TC and EC, other benefits, primarily in terms of adding residual disinfection capacity and the potential removal of other pathogens and larvae, should be highlighted. For example, the access road to the school at Kiranki was flooded for the duration of the study (during the relatively dry non-monsoon season) with a visible presence of bovine livestock and manure, while the tank at Saramthala regularly exhibited a presence of mosquitoes and insects living inside of the tank (Figure 8). Regarding the latter, malaria, dengue fever, chikungunya, Zika virus, and other vector-borne diseases are endemic to the study area (Nanda *et al.* 2017; Kumar *et al.* 2024). Thus, the ability to provide residual disinfection capacity not otherwise present coupled with the reduction of other waterborne and vector-borne pathogens should not be underestimated. Furthermore, as occurred at Saramthala, combining filtration and disinfection is a WASH and HWTS best practice. While some comparative statistical tests of inflow and treated outflow were insignificant at Saramthala (perhaps partly due to the variable of a filtered inflow), TC and EC were still reduced in all samples and residual bactericidal capacity was added, thereby making the water relatively safer to consume from a microbiological perspective. To this end, it should be noted that MadiDrop is designed to only improve microbiological quality. It does not remove turbidity or dissolved pollutants such as nitrate, pesticides, industrial chemicals, or heavy metals. However, in most low-resource settings, the microbiological quality of drinking water is the primary concern.

Turbidity represents a potential caveat. While turbidity was not found to be a significant factor in this study – perhaps due to relatively low (though non-ideal) NTUs – it could impede bacterial reduction in other settings or at different treatment scales/volumes. This is particularly true in cases when surface water, which is likely to be more turbid, is used. Moreover, the variable of turbidity emphasizes the importance of testing the source water *in advance* of deploying MadiDrop (or any treatment technology) and looking for noticeable changes in inflow turbidity throughout the year/seasons.

A final caveat is that this study only tested for coliform bacteria and *Escherichia coli*. While neither of these tests specifically identifies a pathogen, their presence suggests that the water has come into contact with mammalian feces and is therefore at higher risk of having pathogenic microorganisms. In fact, the WHO (2017) recommends <1 EC per 100 mL.

Figure 8 | Photographs of cattle and the flooded access road in front of the school in Kiranki (left) and the interior of the tank at Saramthala that contains biofilm, sludge, and often has mosquitoes and other insects (right).

Greater than 73% of treated effluent samples met this guideline and our mean EC removal rate was >70%, which is comparable to results reported in other published PoU treatment interventions in low-resource settings (e.g., Rosa *et al.* 2010; Juran & MacDonald 2014; Francis *et al.* 2016; Aumeier *et al.* 2017). Furthermore, any decrease in microorganisms improves the (relative) safety of drinking water.

Limitations and future research

This study demonstrates some limitations and there are several avenues for future research. The water quality intervention was a pilot study and deployment at the community scale was novel; these factors enabled the research team to garner much knowledge and lessons learned. First, the length of study and number of schools/tanks involved could be greater. To that point, future research should engage more schools/tanks for a longer duration of time. Temporally, conducting the intervention at different times of the year (e.g., during the monsoon and dry season and periods when source water quality fluctuates) would also be valuable. Pragmatically, in order to vertically position the MadiDrop tablets in the tanks, we suggest utilizing 3D printing to develop long 'sleeves' that the tablets can be inserted into at incremental distances.

Testing for reductions in other health hazards, particularly viruses (e.g., rotavirus), protozoa (e.g., *Cryptosporidium*), and mosquito larvae, is another avenue for more in-depth research. Additionally, the approach could be expanded to similarly situated contexts where drinking water is served from tanks, such as hospitals, restaurants, government buildings, dormitories, office towers, daycares, apartment buildings, and independent houses that have private tanks (often located on the roof). Finally, augmenting the disinfection range and capacity of the MadiDrop technology itself represents a pathway forward in environmental engineering. MadiDrop currently releases only silver ions. However, ongoing research is investigating the delivery of silver in combination with copper ions (Harris *et al.* 2024) as well as hypochlorous acid. The synergistic capabilities of these disinfectants would allow for the elimination of a greater range of pathogens while simultaneously allowing for each disinfectant to be managed at a low-to-moderate level (since all would be working together) in efforts to more easily maintain safe drinking water quality.

CONCLUSIONS

In many low- and middle-income countries, schools serve untreated drinking water that has been pumped into storage tanks. Because the water is often of poor quality, pathogens may be present that cause gastrointestinal infections, potentially leading to missed school days, stunted growth, cognitive impairment, and in extreme cases, death. Given this backdrop, we evaluated the effectiveness of MadiDrop, a novel silver–ceramic technology, at disinfecting drinking water served from tanks at schools in rural, water-scarce India. While silver ionization has been proven effective at the household scale, relatively scarce research has been conducted on its effectiveness at the community level.

Statistical analyses determined that TC concentrations were significantly reduced when comparing inflow samples to outflow samples treated with MadiDrop in two of three intervention tanks and among the overall set of tanks. Additionally, TC was significantly reduced when comparing treated outflow samples to baseline outflow samples across all tanks and as an overall set. For EC, while concentrations were reduced in treated outflow samples compared to inflow samples both overall and in two of two tanks, none of the comparisons were significant. However, EC reduction was significant in two of three intervention tanks and overall when comparing treated outflow samples to baseline outflow samples. In terms of bacterial reductions, TC was reduced across all intervention tanks and by >63% overall, while EC concentrations were reduced across two of two tanks and by >70% overall. TC concentrations were negatively correlated with tank residence time (i.e., contact time with MadiDrops) and silver concentration levels. No relationship was identified between turbidity and MadiDrop's ability to remove TC and, importantly, no effluent samples exceeded the WHO drinking water quality guideline of 100 μg/L of silver ions.

Several practical and technological barriers were identified, including modeling or estimating the number (and vertical placement) of MadiDrops required and the capability to measure effluent silver concentrations. The latter requires access to a laboratory, silver standard solution, and various equipment and consumables, all of which may be unavailable/inaccessible or cost-prohibitive in low- and middle-income countries. Tank management is critical, especially if water sits in a tank over the weekend, a holiday, or similar school closure. Implementing silver ionization at the community scale also surfaced the issue of 'tank ecology' and that pathogens and health hazards may already be present in the tank and premise plumbing in the form of biofilm and sludge. Therefore, the best practice of a joint-treatment approach (e.g., combining filtration and disinfection) signifies a promising HWTS method for localized, community-level water treatment, and such an approach also imbues water with residual bactericidal capacity. Several suggestions for future field-based research were posited, including a longer study period that includes more schools and/or community contexts such as hospitals, restaurants, dormitories, and private rooftop tanks. A temporal scale that incorporates different seasons (i.e., when there are changes in source water quality) would also be insightful. Ultimately, in the Anthropocene that we inhabit, hydrological perturbations and extreme weather resulting in disasters, electrical outages, and intermittent water supplies are all too real. In such cases, community-scale deployment of silver ionization and similar technologies could represent a palatable and contextually appropriate coping mechanism.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Aumeier, B. M., Jiang, X., Djeljadini, S., Smeets, P., Yüce, S., Kazner, C. & Wessling, M. (2017) Evaluating water purification at household level in India, *Desalin. Water Treat.*, **91**, 311–319. https://doi.org/10.5004/dwt.2017.20802.

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T. & Bartram, J. (2014) Fecal contamination of drinking water in low- and middle-income countries: A systematic literature review and meta-analysis, *PLoS Med.*, **11** (5), e1001644.

Bhardwaj, A. K., Sundaram, S., Yadav, K. K. & Srivastav, A. L. (2021) An overview of silver nano-particles as promising materials for water disinfection, *Environ. Technol. Innov.*, **23**, 101721.

Crider, Y., Sultana, S., Unicomb, L., Davis, J., Luby, S. P. & Pickering, A. J. (2018) Can you taste it? Taste detection and acceptability thresholds for chlorine residual in drinking water in Dhaka, Bangladesh, *Sci. Total Environ.*, **613–614**, 840–846.

Ehdaie, B., Rento, C. T., Son, V., Turner, S. S., Samie, A., Dillingham, R. A. & Smith, J. A. (2017) Evaluation of a silver-embedded ceramic tablet as a primary and secondary point-of-use water purification technology in Limpopo Province, S. Africa, *PLoS One*, **12** (1), e0169502.

Francis, M. R., Sarkar, R., Roy, S., Jaffar, S., Mohan, V. R., Kang, G. & Balraj, V. (2016) Effectiveness of membrane filtration to improve drinking water: A quasi-experimental study from rural Southern India, *Am. J. Trop. Med. Hyg.*, **95** (5), 1192–1200. doi: 10.4269/ajtmh.15-0675.

Goel, I., Sharma, S. & Kashiramka, S. (2020) The Water Poverty Index: An application in the Indian context, *Nat. Resour. Forum*, **44**, 195–218. https://doi.org/10.1111/1477-8947.12192.

Gupta, S., Satankar, R. K., Kaurwar, A., Aravind, U., Sharif, M. & Plappally, A. (2018) Household production of ceramic water filters in western Rajasthan, India, *Int. J. Serv.-Learn. Eng.*, **13** (1), 53–66. https://doi.org/10.24908/ijsle.v13i1.11150.

Harris, J. (2005) Challenges to the commercial viability of point-of-use (POU) water treatment systems in low-income settings, MSc Dissertation, Water Science Policy and Management School of Geography and the Environment, Oxford University.

Harris, J. D., Davis, J., Reese, M., Mannzhi, M. P., Tshidumo, N. M., Mhlarhi, R., Edokpayi, J. N. & Smith, J. A. (2023) Improving antibacterial performance of household water filters with a silver-embedded ceramic tablet, *J. Environ. Eng.*, **149** (7), 04023034. https://doi.org/10.1061/JOEEDU.EEENG-7264.

Harris, J. D., Homola, M. J., Estrella-You, A. & Smith, J. A. (2024) Enhancing microbial disinfection in household water treatment by combining silver-ceramic tablet with novel copper and chlorine technologies, *J. Environ. Eng.*, **150** (7), 04024026. https://doi.org/10.1061/JOEEDU.EEENG-7555.

Hill, C. L., McCain, K. M., Nyathi, E., Edokpayi, J. N., Kahler, D. M., Operario, D. J., Taylor, D., Wright, N., Smith, J. A., Guerrant, R. L., Samie, A., Dillingham, R. A., Bessong, P. O. & Rogawski, E. T. (2020) Impact of low-cost point-of-use water treatment technologies on enteric infections and linear growth among children in Limpopo, South Africa, *Am. J. Tropical Med. Hyg.*, **103** (4), 1405–1415.

Juran, L. & MacDonald, M. C. (2014) An assessment of boiling as a method of household water treatment in South India, *J. Water Health*, **12** (4), 791–802.

Kali, S., Khan, M., Ghaffar, M. S., Rasheed, S., Waseem, A., Iqbal, M. M., Khan Niazi, M. B. & Zafar, M. I. (2021) Occurrence, influencing factors, toxicity, regulations, and abatement approaches for disinfection by-products in chlorinated drinking water: A comprehensive review, *Environ. Pollut.*, **281**, 116950.

Kumar, G., Gupta, S., Kaur, J., Pasi, S., Baharia, R., Mohanty, A. K., Goel, P., Sharma, A. & Rahi, M. (2024) Mapping malaria vectors and insecticide resistance in a high-endemic district of Haryana, India: Implications for vector control strategies, *Malar. J.*, **23** (107). https://doi.org/10.1186/s12936-023-04797-8.

Lipps, W. C., Braun-Howland, E. B. & Baxter, T. E. (2023) *Standard Methods for the Examination of Water and Wastewater*, 24th edn. Washington, DC: APHA Press.

McMichael, C. (2019) Water, sanitation and hygiene (WASH) in schools in low-income countries: A review of evidence of impact, *Int. J. Environ. Res. Public Health*, **16** (3), 359.

Nanda, N., Singh, S. P., Prajapati, B. K., Ranjan, K., Kar, N. P., Sharma, S. K. & Valecha, N. (2017) Entomological determinants of malaria transmission in an epidemic prone area of District Nuh (Haryana state), India, *J. Vector Borne Diseases*, **54** (4), 334–340. doi: 10.4103/0972-9062.225838.

Pacey, A. (1977) Technology is not enough: The provision and maintenance of appropriate water supplies, *Aqua*, **1**, 1–58.

Rivera-Sánchez, S., Ocampo-Ibáñez, I. D., Silva-Leal, J. A., Flórez-Elvira, L. J., Castaño-Hincapié, A. V., Dávila-Estupiñan, A., Martínez-Rivera, J. I. & Pérez-Vidal, A. (2020) A novel filtration system based on ceramic silver-impregnated pot filter combined with adsorption processes to remove waterborne bacteria, *Sci. Rep.*, **10**, 11198.

Rosa, G., Miller, L. & Clasen, T. (2010) Microbial effectiveness of disinfecting water by boiling in rural Guatemala, *Am. J. Trop. Med. Hyg.*, **82** (3), 473–477.

Salehi, M. (2022) Global water shortage and potable water safety; Today's concern and tomorrow's crisis, *Environ. Int.*, **158**, 106936.

Spackman, C. & Burlingame, G. A. (2018) Sensory politics: The tug-of-war between potability and palatability in municipal water production, *Soc. Studies Sci.*, **48** (3), 350–371.

Tanwar, N. & Hooda, B. K. (2018) Aspect based multidimensional poverty status of households in rural and urban Haryana, *Int. J. Agric. Stat. Sci.*, **14** (1), 339–348.

Turner, S. (2023) *Water Disinfectants for the Control of Aedes Aegypti and Engineering Social Justice: A Two-Fold Approach to Addressing Water Insecurity and Vector Control. Doctoral dissertation*. University of Virginia, p. 133. Available at: https://libraetd.lib.virginia.edu/downloads/ww72bc647?filename=1_Turner_Sydney_2023_PHD.pdf

World Health Organization (WHO) (2017) *Guidelines for Drinking-Water Quality, Fourth Edition*. World Health Organization, Geneva, Switzerland.

World Health Organization (WHO) (2018) *Alternative Drinking-Water Disinfectants: Bromine, Iodine and Silver*. World Health Organization, Geneva, Switzerland.

Zhao, G. & Stevens Jr., S. E. (1998) Multiple parameters for the comprehensive evaluation of the susceptibility of *Escherichia coli* to the silver ion, *Biometals*, **11**, 27–32.

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