A compact point-of-use water purification cartridge for household use in developing countries

Rajshree A. Patil, Dilshad Ahmad, Shankar B. Kausley, Pradeep L. Balkunde and Chetan P. Malhotra

ABSTRACT

Simple, low-cost household interventions are known to be effective in lowering the incidence of waterborne diseases in developing countries. However, high costs along with operational and maintenance issues have prevented the successful adoption of these interventions among the affected communities. To address these limitations, a cost-effective, gravity-driven water purification cartridge has been developed by employing the synergistic disinfection action of low concentrations of silver and chlorine on bacteria and viruses. The silver and chlorine treatment components within the cartridge have been developed using inexpensive materials and integrated with a life indicator and auto-shut-off-mechanism within a compact form factor. The antibacterial as well as antiviral performance of the cartridge was tested by using ground water spiked with *Escherichia coli* and MS2 bacteriophage. The results show that, although individually, the silver and chlorine treatment systems were unable to inactivate the test strains, the integrated cartridge inactivates both bacteria as well as viruses up to the log reduction requirement of the USEPA guide standard for microbiological water purifiers over its designated life of 2,000 liters.

Key words | chlorine, *Escherichia coli*, MS2, silver, synergistic disinfectant, water purification cartridge

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INTRODUCTION

Clean, safe, and adequate water is a basic human need. However, consumption of water contaminated with microbial pathogens such as bacteria, virus, and protozoan cysts leads to severe waterborne diseases like typhoid, cholera, and hepatitis. Globally, around 780 million people lack access to safe drinking water and 1.8 million deaths occur annually due to waterborne diseases, out of which most are children under the age of five (WHO 2007; UNICEF/WHO 2012). The reported data show that the number of deaths due to waterborne diarrheal diseases is disproportionately inclined towards the developing world, where the number of diarrheal episodes in children is ten times greater than that of children in developed countries (Peterson *et al.* 2008). The most affected communities are those who reside in rural areas, where, due to lack of infrastructure and inadequate funds, it is not possible for the local governmental bodies to construct centralized water treatment plants and provide safe drinking water via a piped distribution network (Bates 2012).

In such regions, point-of-use (POU) water treatment purifiers or methods can prove to be a viable option and an effective means of reducing the incidence of waterborne disease by empowering people to treat their water themselves at their homes (Sobsey *et al.* 2008). Several such POU purifiers are available in developing countries ranging from the affordable to the premium. Most premium purifiers are based on ultraviolet and reverse osmosis treatment which require electricity as well as running tap water for their operation, facilities which are not available in most rural areas of developing countries. Even relatively inexpensive gravity-driven purifiers based on chemical disinfection are only affordable to the middle class residing in urban

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areas of developing countries. It is also difficult to obtain replacement parts for POU purifiers in rural areas causing the purifier to become unusable after some time (Houmann 2012).

To break cost barriers, several cost-effective POU purifiers constructed using locally available low-cost materials have been deployed by various non-governmental organizations (NGOs) in rural areas of developing countries (Johnson *et al.* 2008). Most common among these purifiers are modified clay pots or ceramic filters. However, the microbial reduction performance of such purifiers is often not as per international standards such as those prescribed by the USEPA Guide Standard and Protocol for Testing Microbiological Water Purifiers (USEPA 1987; Brown & Sobsey 2010) which recommends a 6 $\log_{10}$ reduction of bacteria, a 4 $\log_{10}$ reduction of virus, and a 3 $\log_{10}$ reduction of protozoan cysts. Also, apart from being cumbersome to maintain and operate due to their bulkiness and fragile construction, these purifiers often suffer from problems such as poor flow rate and premature clogging (Halem *et al.* 2009). Use of chlorine tablets or chlorinated solutions is another cost-effective means for improving quality of water with the added benefit of leaving a residual disinfectant concentration that can protect against re-contamination. However, these tablets or solutions are formulated to release high doses of chlorine and alter the taste and odor of the water which is often not acceptable to end users and hence their proliferation has been limited (Tebbut 1992; Loo *et al.* 2012). Similarly, there are risks associated with the improper handling of these chemicals due to the high prevalence of illiteracy among rural communities in developing countries. These and other issues discourage people from incorporating the means of POU water purification in their daily life which is already heavily burdened by earning their basic livelihood.

Keeping in mind the different issues associated with the acceptance of low-cost POU water purification methods by those who need them the most, our goal was to develop a low-cost, maintenance-free, and robust water purifier for treating relatively large volumes of water with consistent flow rate at a performance which meets international standards for reduction in bacteria and viruses.

One of the approaches to achieve this balance is the use of synergistic action of disinfectants, where instead of using a single disinfectant to purify the water, applying low concentrations of two or more disinfectants simultaneously or sequentially can result in an overall inactivation of microbial pathogens greater than the sum of the inactivation achieved by each disinfectant individually even when used at high concentrations (Solsona & Méndez 2003). In addition to reducing issues associated with taste and odor, the use of lower concentrations of two or more disinfectants could also eliminate the need to incorporate additional accessories, such as polishing units, which are generally added to chemical-based purifiers to remove excess disinfectant from treated water and are a major contributor to the increased cost and size of these purifiers.

There are several reports in the literature which describe the improvement in efficacy of a combination of disinfectants on pathogen inactivation during the treatment of water. For example, Worley & Williams (1988) report a higher level of inactivation by a mixture of free chlorine and organic *N*-halamine against *Staphylococcus aureus* within a shorter contact time. Synergism in the action of chlorine and monochloramine against *Escherichia coli* and that of chloramine and cupric chloride against the MS2 coliphage has also been reported by Kouame & Haas (1991) and Straub *et al.* (1995).

Metallic silver and copper coupled with halogens are also known to display synergistic action against microorganisms. For example, Landeen *et al.* (1989) showed increased inactivation rates and greater $\log_{10}$ reductions of *Legionella pneumophila* at 400 and 40 mg/L of copper and silver and low levels of free chlorine in the range of 0.1 to 0.4 mg/L. Similar results have been observed by Yahya *et al.* (1990, 1992) against *Staphylococcus* species, coliphage MS2, and poliovirus type 1 by a combination of electrolytically generated copper and silver (400 and 40 mg/L, respectively) and free chlorine (0.3 mg/L).

On similar lines, we have undertaken studies of the individual and combined action of silver and free chlorine against the bacterial test culture *E. coli* ATCC 11229 at concentrations below their regulatory and aesthetic limits, for example, $\leq$100 μg/L for silver and 0.2 mg/L for chlorine. At these concentrations, silver and chlorine do not result in any negative health or esthetic effects on humans and hence do not need to be removed from water post-treatment. The results reveal that a combined action of silver below

100 μg/L and chlorine at 0.2 mg/L was able to achieve a >6 $\log_{10}$ reduction of *E. coli* ATCC 11229 within a short contact time as compared to the individual action of silver or chlorine alone which resulted in inactivation of microbial contaminants at a level of 1 log and 4 log respectively.

Encouraged by the above results, we have developed a water purification cartridge based on the synergistic action between low concentrations of silver and chlorine. The cartridge is in the form of a compact cylinder that can be attached to any suitable reservoir of untreated water and is able to purify 2,000 liters of water while meeting bacteria and virus reduction requirements specified by the USEPA. The purifier was constructed using inexpensive raw materials such as rice husk ash (RHA) and clay impregnated with nano-silver in combination with tablets containing trichloroisocyanuric acid (TCCA). The current paper describes the design and development of the different components of the purification cartridge as well as its flow, disinfectant release, and microbiological inactivation performance over its designated life of 2,000 liters.

METHODS

Design of water purification cartridge

Figure 1 shows a schematic diagram of a water purification cartridge developed in the form of a cylinder 8 cm in diameter and 7 cm in height. Within the cartridge, water gets purified in two stages. The first disinfection stage comprises a nano-silver treated porous disc which is sufficiently porous to allow free flow of water throughout its life. The second disinfection stage comprises a chlorine release system which adds 0.2 to 0.5 mg/L of free chlorine to the silver treated water. The detailed process of producing the nano-silver treated porous disc and the chlorine release system as well as the water flow path within the cartridge are described below.

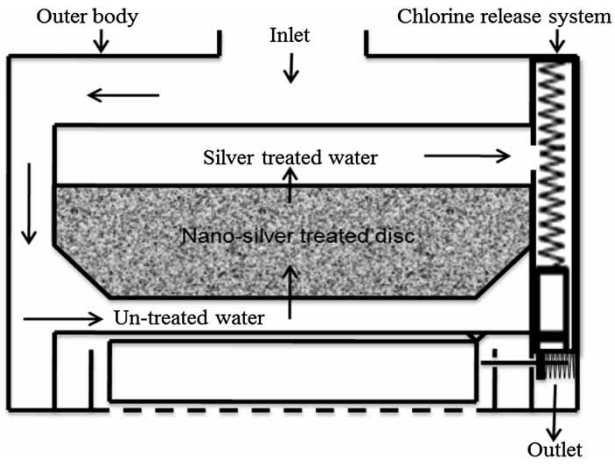

Figure 1 | Design of water purification cartridge and water flow path through it.

Fabrication of nano-silver treated porous disc

The first purification stage comprises a compact nano-silver treated porous disc made using RHA and clay and sintered in a furnace. RHA is an agricultural waste obtained after burning rice husk in rice mills and contains about 90–98% silica, the remainder being carbon, Fe_2O_3, Al_2O_3, CaO, and MgO (Singh & Singh 2011). The amorphous silica present in RHA forms a good medium for water purification due to its high surface area over which metals can be readily bonded (Adam *et al.* 2006). The RHA used in the current study was obtained from a rice mill in Hyderabad, India. The RHA was first cleaned to remove any extraneous matter such as un-burnt husk and then washed with tap water to remove traces of metal oxides present in it. The washing was carried out by soaking the RHA in 1:10 (w/v) water for 1 hour with intermittent stirring. The water was then drained and the RHA was dried in an oven at 150 °C. The dried RHA was sieved to obtain a $-425 + 212$ μm fraction which was found to be most suitable for fabrication of the porous disc. White clay, for example, kaolin, was ground and sieved to obtain particles of mesh size −212 μm. The size fraction of RHA and clay used during fabrication of the disc were optimized to generate pores within the disc during sintering of a size that is sufficient to allow free flow of water over the life of the cartridge. Impregnation of nano-silver within the RHA was carried out by a procedure which is similar to that described by Sastry *et al.* (2012). A 2,000 mg/L solution of silver nitrate was first prepared in distilled water. To this a 1% chitosan solution (prepared in 5% (w/v) citric acid solution in distilled water) was added as a stabilizing agent so as to obtain a final concentration of 120 mg/L chitosan in the silver nitrate solution. The sieved RHA was then added to this solution

and allowed to soak for 2 hours at ambient temperature with occasional stirring. The mixture was then boiled with continuous stirring and a 5% tri-sodium citrate solution was slowly added to it to achieve a final concentration of 420 mg/L of trisodium citrate in the bulk. The trisodium citrate reduces the silver ions to nano particles of metallic silver which remain embedded within the RHA particles. The boiling was further continued for another 20 minutes and the mixture was allowed to soak for about 10–12 hours. The wet nano-silver impregnated RHA was then dried for 12 hours in an oven at 150 °C. The impregnation of nano-silver onto the clay was carried out by following a procedure similar to the process of impregnation of nano-silver on to RHA except that the clay was pretreated with APTES (3-aminopropyl tri-ethoxysilane) to enhance the binding of silver on to the surface of clay. The pretreatment of clay with APTES was carried out by mixing clay and a 1% aqueous solution of APTES in a 1:1 (w/v) ratio to form slurry. After uniform mixing, the APTES-treated clay-slurry was kept at ambient temperature for 3 hours and subsequently dried in an oven at 150 °C for 24 hours. The dried mass of clay was ground and sieved to produce particles in the size range of −212 μm (Patil *et al.* 2013). The nano-silver impregnated RHA and clay were then used to fabricate porous discs as described below.

The silver treated RHA and clay were mixed in a ratio of 7:3 w/w. An amount of water equal to 70% of weight of the dry mixture was added to the RHA and clay and mixed to produce a homogeneous mass. Sixty grams of this wet mixture was compacted in a circular mold under 100 kg pressure. The resultant wet disc was then dried in an oven at 150 °C for 3 hours. The dried disc was then heated at 1,100 °C for 3 hours in a muffle furnace to obtain a sintered disc of 7.5 cm diameter and 2 cm height, as shown in Figure 2.

Figure 2 | Nano-silver treated porous disc.

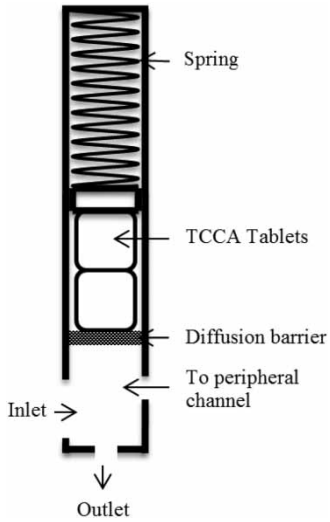

Figure 3 | Chlorine release system.

Chlorine release system

The second purification stage comprises a chlorine release system in the form of a cylindrical housing and two chlorine tablets made of TCCA held in place by a spring, as shown in Figure 3. The system is designed to add chlorine in the range of 0.2–0.5 mg/L into the water flowing at rates which can vary from 0 to 8 Lph (liters per hour). TCCA was used as the source of chlorine due to its stability and high chlorine content per unit mass, that is, ≥90%. The TCCA tablets of dimension 0.5 cm (diameter) × 0.5 cm (height) were produced using a manual hydraulic press and a custom-machined stainless-steel die-punch under a compression pressure of 1.5 ton. The addition of chlorine was achieved by allowing the bottommost tablet to dissolve as water flows next to its bottom surface. TCCA has a solubility of 0.2% (2,000 mg/L) and thus when water comes in contact with the tablet, this leads to a concentration of chlorine in the water which is much higher than the required concentration of 0.2 mg/L. Therefore, it was necessary to slow down the rate of dissolution of the tablet from its bottom surface. This was accomplished in four steps. First, the compaction pressure used for fabricating the tablet was optimized to generate sufficient cohesion force between the

TCCA particles to restrict the dissolution of the chemical at a high rate. Second, the diameter of the tablet was kept as minimal as possible without losing stability which results in limited dissolution of chemical from the bottom surface of tablet. The tablet used here releases 2–2.5 mg/L of chlorine when it comes into contact with water. Third, the direct dissolution of TCCA into the water was controlled by placing a diffusion barrier in the form of a nonwoven cloth in between the tablet surface and the water stream. With the diffusion barrier in place, the chlorine concentration in water is lowered to 0.8–1 mg/L. Lastly, in order to further lower the concentration of chlorine in water, the output stream from the tablet is further diluted by allowing it to mix with a portion of silver treated water which bypasses the chlorine treatment system to the outlet via a peripheral channel. When this bypassed water is mixed with the chlorine containing water, the resultant chlorine concentration is in the required range of 0.2–0.5 mg/L.

Water flow path

The water flow path within the cartridge is as shown in Figure 1. During operation, water enters the cartridge via the inlet and travels through the nano-silver treated porous disc in an upward direction. While traveling through the disc the microbial contaminants present in water get exposed to a very high local concentration of nano-silver, that is, 12 mg per cm^3 where they either get inactivated or injured. A small concentration of silver in the range of 10–70 μg/L also gets added to the water in the form of silver ions (Ag^+) as the water travels through the disc and keeps acting against the surviving bacteria and viruses. The silver treated water then enters the chlorine release system. The microorganisms that were not inactivated by the disinfection action of the silver are inactivated by the disinfection action of chlorine added to the water. Treated water then emerges from the outlet passage and exits the cartridge.

The cartridge is also provided with a life indicator which is attached to the chlorine release system as shown in Figure 4. The life indicator continuously indicates the remaining life of the cartridge to the user via the downward movement of a color-coded plunger. In order to ensure pure water to the user at all times, an auto-shut-off mechanism is integrated with the life indicator which stops the flow of water through the cartridge when the TCCA tablets are exhausted. This is accomplished by pinching a rubber tube which carries silver treated water to the chlorine release system between two plungers, one fixed in a tube placed adjacent to the chlorine release system and the other placed above the tablet within the chlorine release system. As the tablets dissolve, the plunger placed above the tablets moves in a downward direction and when the tablets become completely exhausted the edges of the two plungers meet leading to pinching of the soft rubber tube which passes between them.

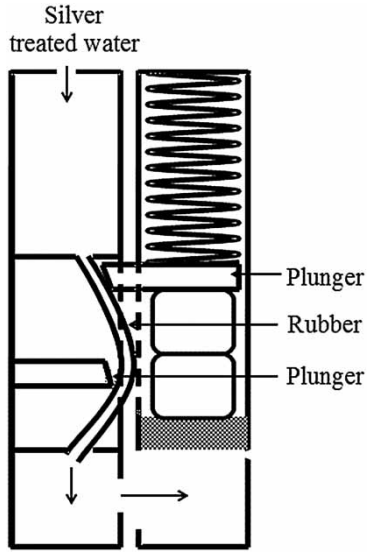

Figure 4 | Life indicator and auto-shut-off mechanism.

Efficacy study

The efficacy testing against bacteria was undertaken by using the bacterial strain *E. coli* ATCC 11229 as recommended by the NSF standard P248 (NSF 2008). A stock culture of *E. coli* was prepared by growing the cells on nutrient agar (Hi-Media, India) at 37 °C for 24 hours. The grown cells were washed off using normal saline (0.85% sodium chloride in distilled water). The culture was centrifuged at 4,500 rpm for 20 minutes. The cell pellets were washed three times by centrifugation at 4,500 rpm for 10 minutes using normal saline. The cell density was adjusted to obtain a final cell concentration of 10^8 to 10^9 colony forming units per milliliter (CFU/mL) using a colorimeter at

450 nm. Ground water was collected from a tube well in Pune, India and was regularly tested for pH, turbidity, chlorides, carbonates, bicarbonates, total dissolved solids (TDS), and sulfates. Representative values for these parameters are given in Table 1. Test water was prepared by spiking 15 L of this ground water with the *E. coli* stock cell suspension to achieve a final concentration in the range of 10^6 to 10^7 CFU/mL in the well water. A sample was withdrawn to determine the initial bacterial concentration. The spiked test water was allowed to pass through the test configuration and the effluent (treated water) was sampled after passing approximately 2 liters of untreated water. Before analysis, the effluent samples were neutralized using a 0.1 mL solution (per 100 mL of sample) of sodium thiosulfate (7.8% in distilled water) and sodium thioglycolate (5% in distilled water) to ensure neutralization of residual disinfectants present in the samples. The influent and effluent samples were analyzed by serially diluting all the samples using normal saline and for every dilution 1 mL of the solution was plated on MacConkey's agar using the pour plate method. The plates were incubated at 37 °C for 24 hours and enumerated for surviving bacterial cells in terms of CFU/mL.

The USEPA Guide Standard and Protocol for Testing Microbiological Water Purifiers recommends the use of both rotavirus and poliovirus for testing the efficacy of purifiers. However, the handling of these human enteric viruses is highly regulated in India and requires stringent contamination controls which are only available across a few labs in the country. Thus, a surrogate for human enteric viruses, the MS2 bacteriophage (ATCC 15597-B1), was used to determine performance of the cartridge against viral contaminates as per the NSF P248 protocol for testing Microbiological Water Purifiers for use in Emergency Military Operations (NSF P248 2008). A stock culture of bacteriophage MS2 ATCC 15597-B1 was prepared by using the host *E. coli* C3000 (ATCC 15597) and a double agar overlay method according to United States Environmental Protection Agency (EPA) Method 1601 (USEPA 1601 2001). The host *E. coli* (ATCC 15597) was grown on a nutrient medium to the mid-log phase. The culture was infected with MS2 bacteriophage ATCC 15597-B1 and incubated at 37 °C until lysis was observed. The bacteriophage was extracted using chloroform, and finally re-suspended in normal saline. Enumeration of the resulting bacteriophage suspension displayed a final concentration of 1.0×10^{12} PFU/mL (plaque forming units per milliliter). Virus contaminated test water was prepared by spiking 15 L of test water with the MS2 stock culture to achieve a final MS2 concentration in the range of 10^5 to 10^6 PFU/mL. The procedure used for challenging the test configuration and collection of influent and effluent test samples was similar to that used for the bacteria challenge water. For enumeration of viable MS2 bacteriophage counts, double agar layer procedure was used. Samples were serially diluted in normal saline, mixed 1:1 with host *E. coli* ATCC 15597, added to 7 mL of soft agar (nutrient agar containing 1% agar) and plated onto nutrient agar plates. The plates were incubated at 37 °C for 16–20 hours, and plaques were enumerated in PFU/mL.

The effectiveness of the system against both *E. coli* and MS2 bacteriophage was expressed in terms of $\log_{10}$ reduction values.

Table 1 | Test water parameters

Parameter	Representative value	Unit
pH	8.1	–
Turbidity	0.31	NTU
Chlorides	23	mg/L
Carbonates	12	mg/L
Bicarbonates	234	mg/L
TDS	423	mg/L
Sulfates	126	mg/L

Experimental

Initially, batch disinfection experiments were used to evaluate synergism between silver and chlorine. During the test, the action of 0.05 and 0.1 mg/L of silver ions individually and in combination with 0.2 mg/L of free chlorine was tested against the bacterial test culture *E. coli* ATCC 11229 at a 30 minute contact time. The study was conducted by preparing five different test systems: 0.05 mg/L silver ions, 0.1 mg/L silver ions, 0.2 mg/L free chlorine, 0.05 mg/L silver ions in combination with 0.2 mg/L free chlorine, and 0.1 mg/L silver ions in combination with 0.2 mg/L free chlorine in 5 L of ground water. Each system was

spiked with the *E. coli* ATCC 11229 stock cell suspension to achieve a final concentration of 10^6 CFU/mL and a sample was withdrawn for determining the initial bacterial concentration. The test systems were stirred intermittently and after a 30 minute contact time a sample was withdrawn from each system, neutralized and analyzed for surviving bacterial population.

After the batch disinfection experiments, individual silver and chlorine treatment systems were prepared and assembled in a test configuration, as shown in Figure 5, in order to study the efficacy of the individual systems as well as the synergistic action between the two systems against the bacterial test strain *E. coli* ATCC 11229. The test configuration comprises a reservoir with two outlets at its bottom. Each outlet was connected to the individual silver and chlorine treatment systems via plastic tubing. These tubes were provided with controllers for controlling and stopping flow of water through them. Initially, the systems were tested as per the configuration shown in Figure 5(a), where the contaminated water enters into the individual systems via separate inlets, exits from the outlet of each system and is collected for determination of bacterial count. The combination of the two systems was tested as per the configuration shown in Figure 5(b). Here, the silver treated water from the first stage was allowed to flow through the chlorine release system and was subsequently collected for bacterial analysis. The bacterial analysis of the treated water exiting from the outlet of each system as well as the integrated system was carried out at four different contact times, that is, 0.5, 1, 2, and 3 hours, in order to compare the kinetics of bacterial inactivation in water treated by the individual systems as well as the integrated system.

After confirming the synergistic action between silver and chlorine release systems with *E. coli* ATCC 11229, the complete cartridge (Figure 1) was tested against *E. coli* ATCC 11229 as well as MS2 bacteriophage ATCC 15597-B1 by attaching it at the bottom of a source container placed on a collection container as shown in Figure 6. The source container was also provided with primary and secondary pre-filters to trap coarse and fine particulate matter present in the well water before it flows into the purification cartridge as shown in Figure 6.

At different stages during the life of the purification cartridge, test water artificially spiked with *E. coli* ATCC 11229 and MS2 bacteriophage ATCC 15597-B1 was manually fed into the top container through the primary pre-filter and treated water was collected from a tap attached to the collection container for analysis of surviving populations of bacteria and viruses.

Determination of residual disinfectant concentrations and flow rate of the cartridge

In order to determine the residual concentration of disinfectants added by the cartridge to the water, effluent samples

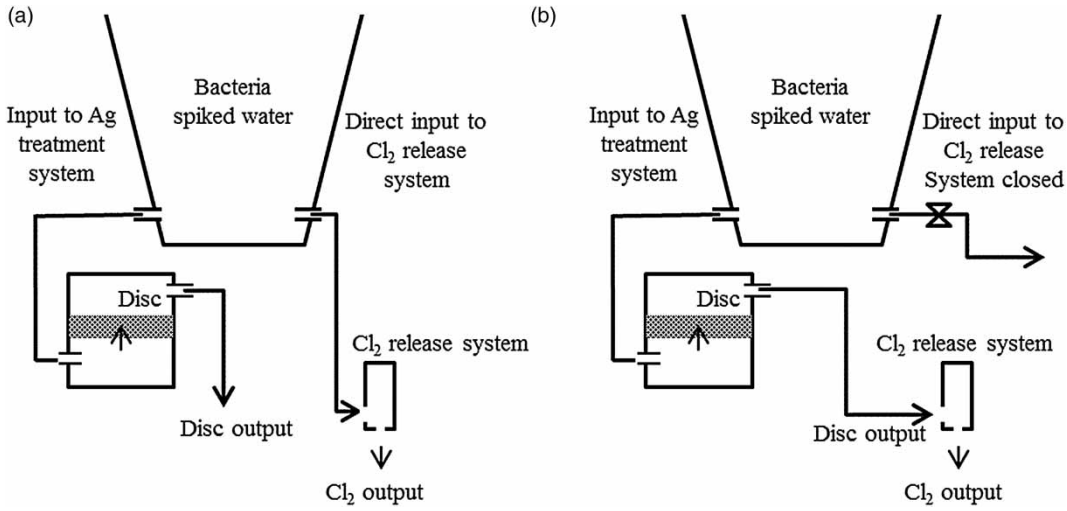

Figure 5 | Test configuration for testing performance of purifier components: (a) individual systems, (b) integrated system.

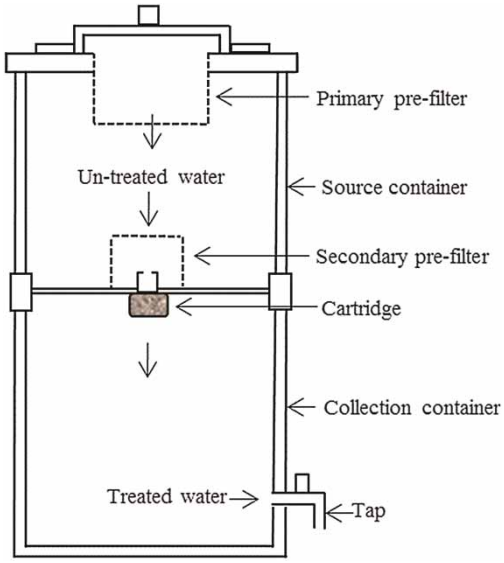

Figure 6 | Configuration for testing the water purification cartridge.

were periodically collected and analyzed for the presence of silver and chlorine by using an atomic absorption spectrophotometer (AAS, GBS Scientific) and a liquid chemical reagent (Chlortest, Merck, India), respectively. Also, at regular time intervals, the flow rate (in Lph) of the purifier was recorded under a water head of 10 cm, which corresponds to one-third of the total water head available in a typical source container, so as to ensure adequate flow rate from the purifier even when the source container contains a low volume of water.

RESULTS

Synergism between silver and chlorine

The results of batch disinfection tests performed to demonstrate synergism between low concentrations of silver and chlorine are depicted in Table 2.

As seen in Table 2, silver ions at a concentration of 0.05 mg/L exhibit no inactivation of *E. coli* ATCC 11229 and even at a concentration of 0.1 mg/L (the minimum contaminant level (MCL) of silver ions in drinking water) are able to achieve only $\geq$1 log reduction. Chlorine alone at a concentration of 0.2 mg/L shows $\geq$4 log reduction but in combination with just 0.05 mg/L of silver ions shows

Table 2 | Synergistic action of silver (Ag) and chlorine (Cl_2)

Disinfectants	Concentration (mg/L)	Bacteria input (CFU/mL)	Contact time (minute)	Log reduction
Ag	0.05	1.6×10^6	30	0
Ag	0.1	1.6×10^6	30	1.37
Cl_2	0.2	1.6×10^6	30	4.44
$Ag + Cl_2$	$0.05 + 0.2$	1.6×10^6	30	6.20
$Ag + Cl_2$	$0.1 + 0.2$	1.6×10^6	30	6.20

>6 log reduction within a 30 minute contact time. The above data confirm synergistic action between low concentrations of silver and chlorine within their individual MCLs in being able to inactivate the test bacterial strain up to the limit prescribed by the USEPA guide standard.

Table 3 shows the bacteria reduction performance of the individual silver and chlorine release systems and the combined system as per the test configurations shown in Figure 5. The table gives bacterial reduction performance of each system at different points of water flow at different contact times of 0.5, 1, 2, or 3 hours. The table also gives the concentrations of the residual disinfectants, that is, silver and chlorine in the effluent water samples during the efficacy study.

As seen from Table 3, the silver treatment system shows lower bacterial reduction performance as compared to the chlorine release system throughout the testing period. The water treated by the silver treatment system shows <1 $\log_{10}$ reduction up to 1 hour contact time at all points except near the end of the study where 1,676 liters of water has flowed through the system. At 2 and 3 hours contact time the system displays an enhancement in bacterial reduction performance where the reduction is in the range of 2 to 5 $\log_{10}$. However, except at one data point, that is, 1,676 liter of water flow, the silver treatment system was unable to achieve the required 6 $\log_{10}$ reduction even after 3 hours of contact time. As opposed to the silver treatment system, the chlorine addition system was able to achieve a bacterial reduction performance in the range of 4 to 5 $\log_{10}$ within a 1 hour contact time throughout the study. After 2 hours of contact time chlorine alone can achieve bacterial reduction nearly approaching 6 $\log_{10}$. The integrated silver and chlorine treatment systems when tested

Table 3 | Study of synergism between silver and chlorine treatment system

		Bacterial reduction performance of silver treatment system				Bacterial reduction performance of chlorine release system				Bacterial reduction performance of combined silver and chlorine release system					
		Log_{10} reduction at different contact time (in hours)				Log_{10} reduction at different contact time (in hours)				Log_{10} reduction at different contact time (in hours)					
Water flow (L)	Input CFU/mL	0.5	1	2	3	0.5	1	2	3	0.5	1	2	3	Ag μg/L	Cl_2 mg/L
91	5.77×10^6	0.64	0.94	3.05	5.28	4.42	4.7	5.59	5.86	6.76	5.46	6.76	6.76	18	0.2
264	5.21×10^6	0.31	0.44	0.55	3.13	6.11	4.87	6.72	6.72	6.72	6.72	6.72	6.72	30.6	0.2
501	3.64×10^6	0.39	0.73	2.87	4.52	4.54	4.85	5.56	6.08	6.56	6.56	6.56	6.56	10.9	0.2
859	3.99×10^6	0.87	0.93	2.21	2.58	3.57	4.35	5.11	6.6	5.9	6.6	6.6	6.6	20	0.2
1372	5.13×10^6	0.73	1.03	1.32	3.34	4.86	5.81	6.41	5.71	6.71	6.71	6.71	6.71	9	0.2
1676	3.54×10^6	0.9	2.2	6.5	6.5	2.4	3	4.5	5.9	6.5	6.5	6.5	6.5	32.3	0.2

together show considerable enhancement in bacterial reduction performance where $\geq$6 log_{10} reduction was achieved within 30 minutes of contact time throughout the study period. The efficacy data as obtained above indicate synergistic action between silver and chlorine, where the two disinfectants when combined in low concentrations give the desired performance as opposed to the individual disinfectants when employed separately.

Bacterial and virus reduction performance of purification cartridge

Figure 7 shows the performance of the purification cartridge (Figure 1) against *E. coli* ATCC 11229 and MS2 bacteriophage ATCC 15597-B1 at different points during the test period up to 2,500 liters of water flow. As seen from Figure 7, the purifier was determined to be fully effective for inactivating the test bacterial and bacteriophage strains and consistently met the 6 log_{10} and 4 log_{10} reduction requirements recommended by USEPA standards for microbiological purifiers up to 2,500 liters of water flow through the cartridge.

Residual disinfectant concentrations and flow rate of the cartridge

Figure 8(a) shows silver and chlorine release patterns of the water purification cartridge during the test period. The cartridge shows consistent release of silver below 0.1 mg/L, that is, 100 μg/L and chlorine in the range of 0.2–1 mg/L throughout the life of the cartridge. These disinfectant concentrations are below their permissible limits in drinking water, that is, 100 μg/L for silver and 4 mg/L for chlorine (USEPA 2009), and hence the purified water is safe for consumption as it is.

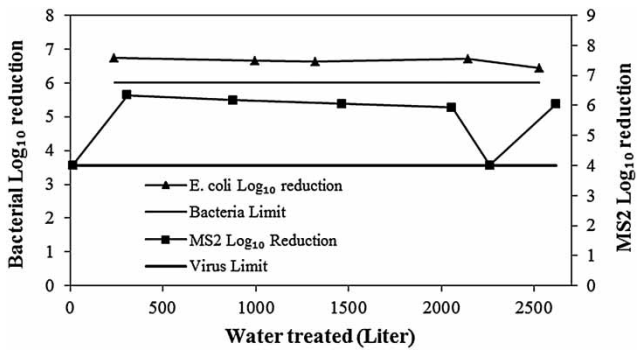

Figure 7 | Performance of purification cartridge against *E. coli* ATCC 11229 and MS2 bacteriophage ATCC 15597-B1.

Figure 8(b) shows the flow rate of the water purification cartridge under a 10 cm water head over 2,500 liters which shows that the cartridge can treat water at a flow rate in the range of 6–7 Lph without clogging.

DISCUSSION

The major goal of our work was to address the barriers related to affordability and acceptance of POU treatment

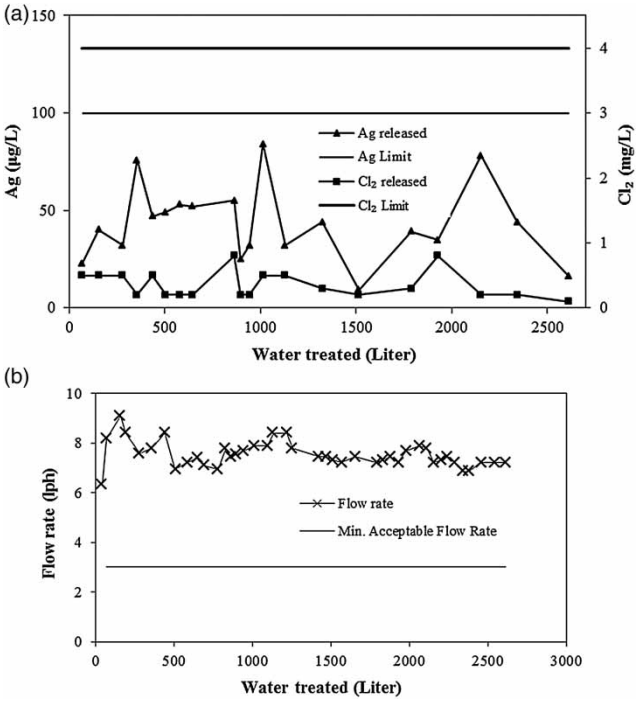

Figure 8 | Performance of water purification cartridge: (a) disinfectant release, (b) flow rate.

methods among low-income rural and urban households in developing countries by developing a cost-effective, user-friendly, robust and compact water purification cartridge which can meet USEPA standards for microbial reduction. This has been accomplished by employing the synergistic disinfection action between low concentrations of silver and chlorine on bacteria and viruses by developing two independent systems for exposing the microorganisms to two different disinfectants at concentrations below their regulatory limits in drinking water and integrating them in a compact cartridge. Silver is known to be a clean disinfectant as it does not add taste, odor, or color to the treated water and, more importantly, does not produce any harmful by-products after disinfection (Ericsson *et al*. 2002). Several low-cost purifiers, such as clay pot filters and ceramic candle filters, are coated with silver salts for imparting bacteriostatic properties to them (Silvestry-Rodriguez *et al.* 2007). However, being mostly a bacteriostatic agent, silver requires high concentrations and contact times for its activity and is not recommended as a primary disinfectant during treatment of highly contaminated water (Sobsey 2002). Conversely, chlorine is a highly potent disinfectant as compared with silver and is effective against a number of microbial contaminants in a short contact time. A residual concentration of chlorine can also protect water from subsequent re-contamination. This quality is important because often the original water source may not be contaminated but water contamination may occur during transport or storage in the home. Chlorine is also a cheap and safe method to treat water. However, regular use and accurate addition of chlorine can be complicated for people living in rural areas. Similarly, manual errors in addition of chlorine either in the form of solid powder, tablets, or liquid solution leads to water that is either under-chlorinated and therefore not fully disinfected or over-chlorinated to the point that it is unpalatable, discouraging the direct use of chlorine in rural households. Moreover, the use of high concentrations of chlorine in water containing organic matter is associated with the generation of carcinogenic by-products (Nieuwenhuijsen *et al*. 2009). This necessitates the removal of chlorine from water before it is consumed by employing a secondary polishing step. A few purifiers based on the addition of chlorine to water are available in the Indian market; however, due to the requirement of a bulky and expensive polishing system to remove the excess chlorine the cost of such purifiers is still beyond the reach of the target populations.

By employing the synergism between low concentrations of silver and chlorine we have addressed the limitations of using these disinfectants individually for POU water treatment. Our study shows that a combination of low concentrations of silver and chlorine yields additive effects on the inactivation of *E. coli* and MS2. Another benefit is that the low concentrations (silver in the range of 10–70 µg/L and chlorine in the range of 0.2–0.5 mg/L) are well below their acceptable limits (100 µg/L and 4 mg/L, respectively) in drinking water and hence the water treated by the purifier is safe for consumption as it is without the need of removing excess disinfectants from treated water. In addition, most individuals are able to taste chlorine or its by-products at concentrations of 4 mg/L, and some at levels as low as 0.3 mg/L (WHO 2003; USEPA 2009). The concentration of chlorine added to water treated by the current cartridge (0.2–0.5 mg/L) can be considered within the threshold limits for the human detection of taste and odor and hence does not add any adverse esthetics to water and

further eliminates the need of adding a polishing unit in the system. Moreover, the elimination of a polishing unit helps in reducing the overall size of the cartridge. Due to this reduction in size, the amount of plastic required to construct the cartridge is reduced which in turn reduces the cost of the cartridge as well as the cost of manufacturing a purifier based on the cartridge. By incorporating inexpensive raw materials and low concentrations of disinfectants, the cost and size of the purification cartridge is expected to be further reduced to nearly half of that of replaceable cartridges in purifiers currently available in the Indian market. Also, the current cartridge needs negligible maintenance or intervention over its usable life. The availability of such a compact, robust water purification system at a price which is well within the reach of people who do not use water purifiers due to their high cost of acquisition and maintenance is expected to increase adoption of household water purification among low-income households affected most by waterborne diseases.

CONCLUSIONS

A low-cost water purification cartridge has been developed employing synergistic action between low concentrations of silver and chlorine to achieve stringent reduction performance as set by regulatory bodies such as the USEPA. The individual components for treating water with these two disinfectants were developed using inexpensive raw materials and integrated in a compact cartridge. The cartridge is able to treat over 2,000 liters of water contaminated with bacterial and viral contaminates at reduction levels of 6 $\log_{10}$ and 4 $\log_{10}$, respectively. It also incorporates a life indicator and auto-shut-off mechanism to ensure safe water during its usable life. The availability of such a cartridge could provide a good option for improving the quality of water and, in turn, in reducing the incidence of waterborne disease in developing countries.

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