Comparative study of disinfectants for use in low-cost gravity driven household water purifiers

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ABSTRACT

Point-of-use (POU) gravity-driven household water purifiers have been proven to be a simple, low-cost and effective intervention for reducing the impact of waterborne diseases in developing countries. The goal of this study was to compare commonly used water disinfectants for their feasibility of adoption in low-cost POU water purifiers. The potency of each candidate disinfectant was evaluated by conducting a batch disinfection study for estimating the concentration of disinfectant needed to inactivate a given concentration of the bacterial strain *Escherichia coli* ATCC 11229. Based on the concentration of disinfectant required, the size, weight and cost of a model purifier employing that disinfectant were estimated. Model purifiers based on different disinfectants were compared and disinfectants which resulted in the most safe, compact and inexpensive purifiers were identified. Purifiers based on bromine, tincture iodine, calcium hypochlorite and sodium dichloroisocyanurate were found to be most efficient, cost effective and compact with replacement parts costing US$3.60–6.00 for every 3,000 L of water purified and are thus expected to present the most attractive value proposition to end users.

Key words | disinfectant, drinking water, *E. coli*, microbiological purifier, point-of-use water purifier

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NOMENCLATURE

C Disinfectant concentration (mg/L)

D_{p} Diameter of the plastic container (cm)

P_{t} Total cost (US$)

P_{u} Unit cost (US$/kg)

Q Mass of the active disinfectant per unit mass of source chemical (g/g)

r_{hd} Slenderness ratio (H/D ratio)

W Amount (g)

T Contact time for disinfection (minute)

V Volume (cm^3)

Y Adsorption capacity (g/g)

Greek letters

ρ Density (g/cm^3)

Subscripts

ac   Activated carbon

addn   Additional

c   Chemical

ds   Dosing system

H   Health

hd   Height to diameter (H/D)

m   Minimum

p   Plastic

pc   Purification cartridge

pu   Polishing unit

pw   Purified water

sc   Source chemical

MAC   Maximum acceptable concentration

INTRODUCTION

Contamination of drinking water by pathogenic microorganisms represents a major human health hazard in many parts of the world causing diseases such as diarrhea, typhoid, cholera, hepatitis, polio and amoebic dysentery. In order to prevent the spread of waterborne diseases, it is necessary to remove or inactivate pathogenic microorganisms in contaminated water before it is consumed. Methods of treating drinking water include boiling, treating with chlorine, filtering through porous media, passing water through disinfectant impregnated media, membrane filtration, reverse osmosis and exposure to ultraviolet radiation (Peter-Varbanets *et al.* 2009). While most developed countries treat water in a centralized plant before piping it to consumers, in less affluent countries, point of use (POU) household water purification interventions have been found to be capable of dramatically improving the microbial quality of water and reducing the risks of waterborne disease (Brown & Sobsey 2010). Most household POU water purifiers employ chemical disinfectants due to their low cost, convenience, amenability to work under gravity flow and the non-requirement of electricity and piped water. A wide variety of chemical disinfectants such as halogens, metal disinfectants (e.g. silver and copper), ozone, chlorine dioxide and hydrogen peroxide are suitable for disinfecting water. However, many of them are not suitable for incorporation in household water purifiers because of their short shelf life, high cost and difficulties encountered in operation and maintenance of the purifier. The selection of a suitable disinfectant is a key design step in determining the efficiency, size and cost and ultimately commercial success of a purifier. Purifiers targeted at low income households should ideally treat large amounts of water before requiring replenishment of disinfectant cartridge and the disinfectant itself should be potent enough so that a compact cartridge is able to treat water over many months. The disinfectant should also be safe, economical and the resultant purifier should be simple to operate and maintain.

According to the United States Environmental Protection Agency (USEPA) standards for microbiological purifiers (USEPA 1987), the target performance for an effective microbiological purifier is a 6 $\log_{10}$ reduction of bacteria, 4 $\log_{10}$ reduction of virus and 3 $\log_{10}$ reduction of cysts. One approach that can be applied for evaluating a candidate disinfectant for a purifier could be the determination of a minimum concentration of disinfectant required to disinfect a given concentration of microorganisms at the level set by the USEPA standards in minimum contact time. The data on disinfectant concentration could then be used to calculate the amount and cost of disinfectant required to treat contaminated water over the expected life of a purifier cartridge containing the disinfectant. The size and cost data of purification cartridges based on different disinfectants could then be compared to pick disinfectants that are most suitable for low-cost household purification applications. This will reduce the cycle time for developing new low-cost household purifiers.

In the present study, the effectiveness of eight disinfectants was quantified in terms of their concentration and time required to inactivate 10^6 colony forming units (CFU)/mL (6 $\log_{10}$) of the bacterial strain *Escherichia coli* (*E. coli*) ATCC 11229, the test concentration and strain suggested by National Sanitation Foundation (NSF) Standard P248 for testing microbiological purifiers (NSF 2008) which conforms to the USEPA guidelines for microbiological water purifiers (USEPA 1987). The concentration and contact time data were then used to determine the effectiveness, size and cost of resultant household water purifiers employing the candidate disinfectants. Such prospective purifiers were then compared and the disinfectants most suitable for incorporation in low-cost household purifiers were identified.

MATERIALS AND METHODS

Test culture

A stock culture of the bacterial strain *E. coli* ATCC 11229 was grown on nutrient agar (Hi-Media, India) at 37 °C for 24 hours. The grown cells were washed off using normal saline. The culture was centrifuged at 4,500 rpm for 20 min. The pellets of cells were washed twice by centrifugation for 10 min using normal saline. The cell density was

adjusted to obtain a final cell concentration of 10^8–10^9 CFU/mL.

Test disinfectants

The disinfectants and corresponding disinfectant releasing compounds that formed part of the current study were: silver ions via silver nitrate ($AgNO_3$), nano silver (in solution), chlorine (via calcium hypochlorite ($Ca(OCl)_2$), sodium dichloroisocyanurate (NaDCC) and Chloramine-T), iodine (in the form of tincture iodine), bromine (liquid bromine) and hydrogen peroxide (via a 30% hydrogen peroxide (H_2O_2) solution).

Silver (Ag)

A stock solution containing 100 mg/L of silver ions was prepared by dissolving $AgNO_3$ (AR grade, Micron Platers, India) in distilled water. The concentration of silver in the stock solution was confirmed using atomic absorption spectrophotometry (AAS) (GBC-Avanta, Australia). The stock solution was used to prepare test systems containing 0.1, 1, 10 and 20 mg/L of silver ions in water.

Nano silver (nAg)

A 100 mg/L nano silver stock solution was synthesized using $AgNO_3$ as a source of silver ions, tri-sodium citrate (Qualigens, India) as a reducing agent as per the procedure described by Ratyakshi & Chauhan (2009). The formation of nano silver was confirmed using a UV visible spectrophotometer (Perkin Elmer, Lambda 25). The actual concentration of silver in test solution was determined by AAS. The stock solution was used to prepare test systems of concentrations 0.1, 1, 10 and 20 mg/L of nano silver in water.

Chlorine

Three different chlorine releasing compounds were tested in this study, viz. $Ca(OCl)_2$ (33% Cl_2, LR grade, CDH, India), NaDCC (96% purity, AR grade, Sigma Aldrich, USA) and Chloramine-T (99% purity, Loba Chemie, India). Stock solutions containing 100 mg/L Cl_2 were prepared by dissolving the above compounds in distilled water. The stock solutions were used to prepare test systems with Cl_2 concentrations of 0.2, 0.5, 1 and 10 mg/L.

Bromine

Elemental bromine (Qualigens, 99% purity) was used to prepare a 1,000 mg/L stock solution in distilled water. The stock solution was used to prepare test systems of concentrations 0.2, 0.5, 1 and 10 mg/L.

Iodine (tincture iodine)

A stock solution of 2% tincture iodine (2.0% (wt/v) iodine (I_2), 2.4% (wt/v) sodium iodide (NaI) in 50% (v/v) ethanol and 50% (v/v) distilled water) was prepared. The stock solution was used to obtain test systems with free-iodine concentrations of 0.2, 0.5, 1 and 5 mg/L.

Hydrogen peroxide

A 30% H_2O_2 (Qualigens) solution was used to prepare test systems containing H_2O_2 concentrations of 10, 100, 1,000 and 10,000 mg/L.

Batch disinfection study for determining the anti-microbial efficacy of disinfectants

The efficacies of the above disinfectants at different concentrations and contact times were evaluated in a batch disinfection process using ground water as test water. Ground water from wells is the most common source of drinking water in many developing countries and represents challenge water for POU water purifiers since it often contains large amounts of chlorides, sulfates, carbonates and bicarbonates which are likely to interfere with the disinfection process and thus reduce the potency of most disinfectants. Ground water was collected from a tube well in Pune, India and was regularly tested for turbidity, pH, chlorides, conductivity, total dissolved solids (TDS), carbonates and bicarbonates, average values for which are given in Table 1. Test water was prepared by spiking 5 L of ground water with the *E. coli* stock cell

Table 1 | Ground water parameters

Parameter	Average value	Unit
pH	8.0–8.5	–
Turbidity	0.3–1.5	NTU
Chlorides	23.2–51.0	mg/L
Carbonates	224.0–329.5	mg/L
Bicarbonates	12.0–66.0	mg/L
TDS	423.8–585.0	mg/L
Sulfates	36.4–49.2	mg/L

suspension to achieve a final concentration of 10^6 CFU/mL and a sample was withdrawn for determining the initial microbe concentration. Test systems of different disinfectants of different concentrations were prepared by adding required amounts of stock solutions of the disinfectants into the test water and stirred using a glass rod. Ten milliliters of samples were withdrawn from the test systems at time intervals of 10, 30, 60 and 120 min. Before microbiological analysis, the residual disinfectant in the sample was neutralized to avoid overestimation of efficacy of the disinfectant after the given contact period. A 0.1 N sodium thiosulfate solution was used to neutralize halogens while a mixture of 7.8% sodium thiosulfate and 5% thioglycolate was used to neutralize metal disinfectants. The samples were then serially diluted using normal saline and, for every dilution, 1 mL of the solution was plated on MacConkey's agar as per 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 efficacies of different disinfectants at different test concentrations (mg/L) and contact times (minutes) were reported in terms of $\log_{10}$ reduction values. From the efficacy data, the minimum concentration of active disinfectant ($C_{m,c}$) and corresponding contact time (T_m) required to meet the USEPA bacterial reduction requirement of 6 $\log_{10}$ was determined for each of the studied disinfectants.

Procedure for designing a model purifier

The model purifier considered in this study is assumed to be a table-top POU device with a source reservoir for collection of input water, a collection reservoir for collection of purified water, a purification cartridge for disinfection of water and a polishing unit for removal of excess disinfectant from water. The purification cartridge and the polishing unit are considered to be the key functional parts which need to be replaced after their designated life. In the current study, it is assumed that each purification cartridge will be able to purify 3,000 L of water up to the desired level of disinfection before needing a change of cartridge. This capacity is obtained considering an average water consumption of 15 L per day by a family of four over a 6 month period.

Purification cartridge

The purification cartridge disinfects water by continuously releasing a fixed ratio of source chemical into the water which results in a concentration $C_{m,c}$ of active disinfectant in water. The source chemical may be in the form of a concentrated solution or a solid powder compacted in the form of a tablet. The concentration of the source chemical ($C_{m,sc}$) required to maintain a concentration $C_{m,c}$ of active disinfectant in water can be estimated using Equation (1):

$$C_{m,sc} = \frac{C_{m,c}}{Q} \tag{1}$$

where Q represents the mass of the active disinfectant per unit mass of source chemical or the percentage of active disinfectant present in a solution.

The purification cartridge is assumed to consist of a storage unit which stores the entire quantity of source chemical necessary to treat 3,000 L of water. It also houses a chemical dosing system which continuously adds source chemical to water to maintain a concentration of $C_{m,sc}$.

The mass of source chemical (W_{sc}) that needs to be included in a purification cartridge in order to purify 3,000 L can be calculated from $C_{m,sc}$ using Equation (2):

$$W_{sc} = \frac{C_{m,sc} \times 3,000}{1,000} \tag{2}$$

The volume occupied by the source chemical (V_{sc}) can then be calculated using Equation (3):

$$V_{sc} = \frac{W_{sc}}{\rho_{sc}} \qquad (3)$$

where ρ_{sc} is the bulk density of the source chemical from Table 2 where densities and costs of different disinfectant releasing chemicals have been summarized.

The cost of source chemical ($P_{t,sc}$) can then be calculated using Equation (4):

$$P_{t,sc} = W_{sc} \times \frac{P_{u,sc}}{1,000} \qquad (4)$$

where $P_{u,sc}$ is the unit cost of source chemical (US\$/kg) from Table 2.

In this study, the purification cartridge and its internal parts are assumed to be made of a plastic material, ABS (acrylonitrile butadiene styrene). The cartridge is assumed to be in the form of a slender cylindrical container with slenderness ratio, $r_{hd} = 4$. The chemical dosing system within the cartridge is assumed to occupy an additional $V_{ds,pc} = 30$ cc, weigh 30 g and cost US\$0.50. The cartridge also provides for an inlet, an outlet and space for flow of water within

the cartridge which together are assumed to occupy an additional $V_{addn,pc} = 20$ cc.

The diameter of the purification cartridge container ($D_{p,pc}$) can then be calculated by Equation (5) to be:

$$D_{p,pc} = \left(\frac{4 \times (V_{sc} + V_{ds,pc} + V_{addn,pc})}{r_{hd,pc} \times \pi} \right)^{1/3} \qquad (5)$$

The wall thickness of the plastic container is assumed to be 3 mm in order for it to possess sufficient strength to hold chemicals and to withstand the wear and tear of use. The cartridge body is assumed to be sealed with circular plates at its top and bottom. Thus, the volume of plastic material required to prepare a cartridge container can be calculated using Equation (6) to be:

$$V_{p,pc} = \left(\frac{\pi}{4} \left((D_{p,pc} + 0.3)^2 - (D_{p,pc})^2 \right) \times (r_{hd,pc} \times D_c) \right) + 2 \times \left(\frac{\pi}{4} (D_{p,pc})^2 \times 0.3 \right) \qquad (6)$$

The corresponding weight of plastic required to make the cartridge can be calculated using Equation (7) (where ρ_p is the density of plastic) to be:

$$W_{p,pc} = V_{p,pc} \times \rho_p \qquad (7)$$

The cost of plastic ($P_{t,p,pc}$) in the purification cartridge can be calculated using Equation (4) by using the unit cost of the plastic ($P_{u,p}$) from Table 2.

When chemicals are used in the solid form, they are assumed to be bound in the form of a tablet by using suitable binders and additives to control the rate of dissolution of the chemical in water. For simplicity, the combined weight, volume and cost of additive and binder needed to make tablets are assumed to be 3 g, 3 cc and US\$0.0015 per 10 g of source chemical. The total size, weight and cost of the purification cartridge can then be calculated as the sum of the sizes, weights and costs of source chemical, plastic, dosing system, binder and additive (wherever necessary).

Table 2 | Bulk density and cost of different chemicals and materials

Chemical/material	Density (g/cc)	Unit cost (US\$/kg)
$AgNO_3$	4.35 (Perry *et al.* 1997)	1,262 (Ebay 2011)
Nano silver	1.8 (Autofibrecraft 2012)	1,857 (Alibaba 2012)
$Ca(OCl)_2$ (Cl_2-33%)	0.8 (OECD SIDS 2004)	0.4 (Raghavan 2012)
NaDCC (Cl_2-62.5%)	0.95 (Hasa 2011)	1.23 (Alibaba 2012)
Chloramine-T (Cl_2-25%)	1.4 Heneke & Masten (2002)	9 (Alibaba 2012)
Tincture iodine (I_2-2% wt/vol)	0.96 (Medi-Flex 2006)	5.68 (Druginfosys 2012)
Liquid bromine	3.11 (Perry *et al.* 1997)	5.62 (Raghavan 2012)
H_2O_2 (H_2O_2-30% wt/vol)	1.12 (Perry *et al.* 1997)	0.49 (Raghavan 2012)
Activated carbon	0.64[a]	1.5 (Alibaba 2012)
Plastic (ABS)	1.05 (Roy 2011)	2.36 (Raghavan 2012)

[a]Value obtained from laboratory experiment.

Polishing unit

The treated water from a purifier should be safe to drink and should not pose adverse health effects over its prolonged

consumption. Various health effects have been correlated to the consumption of large doses of disinfectants and bypro-ducts of disinfection present in treated water (Richardson 2005). Additionally, treated water should not possess adverse aesthetics such as taste, odor and color. Thus, while using chemical disinfectants, care should be taken that the residual (post-disinfection) concentration of chemicals in the treated water should be within the acceptable safety and aesthetic limits set by standard bodies such as the WHO and USEPA. In this study, the maximum acceptable concentration of disinfectant in the purified water ($C_{MAC,pw}$) is considered as the minimum of the maximum acceptable concentration based on health ($C_{MAC,H}$) and aesthetic effects ($C_{MAC,Aes}$) which are tabulated in Table 3. If the chemical concentration added to water exceeds the maximum acceptable concentration ($C_{MAC,pw}$), then the residual chemical needs to be removed using a suitable polishing unit. In the current study, activated carbon is assumed to be the de-facto polishing medium, as it is commonly used for removal of many organic and inorganic contaminants from water (Sigworth & Smith 1972; Dabrowski *et al.* 2005). The removal capacity of activated carbon for different disinfectants was evaluated by conducting batch adsorption studies where 2 g of activated carbon was soaked in 200 mL of 100 mg/L disinfectant solution for 15 min. The difference in initial and final concentrations of disinfectant in solution was then used to estimate the amount of disinfectant adsorbed by activated carbon and are summarized in Table 4. For hydrogen peroxide-based filters, it is assumed that its complete dissociation in water circumvents the need of a polishing unit.

Table 3 | Maximum acceptable concentration of disinfectants in drinking water

| Disinfectant | Maximum acceptable concentration (mg/L) | |
	$C_{MAC,H}$ (Health)	$C_{MAC,Aes}$ (Aesthetic)
Silver (Ag)	0.1 (USEPA 2012a)	–[a]
Chlorine (Cl$_2$)	4 (USEPA 2012a)	0.2[b] (IS 10500 1992)
Bromine (Br$_2$)	1 (USEPA 1993)	0.2[b] (USEPA 1993)
Iodine (I$_2$)	–[c] (WHO 1996)	0.147–0.204[d] (WHO 1996)

[a]Aesthetic values are not listed if the compound does not cause aesthetic effects.
[b]Typical and required concentration is 0.2 mg/L of chlorine after exposure to disinfectant.
[c]Insufficient data to set a guideline value based on health considerations.
[d]The taste and odor thresholds for iodine.

Table 4 | Experimentally determined values of polishing capacity of activated carbon for different disinfectants

Disinfectant	Polishing capacity (g of disinfectant/g activated carbon)
Silver (Ag)	0.0023
Nano silver (nAg)	0.0028
Chlorine (Cl$_2$)	0.0026
Bromine (Br$_2$)	0.0055
Iodine (I$_2$)	0.0080

The amount of activated carbon (W_{ac}) required to remove residual disinfectant in the purified water throughout the life of purification cartridge, i.e. 3,000 L, can be calculated using Equation (8), where Y_{ac} is the adsorption capacity of activated carbon for a given disinfectant from Table 4:

$$W_{ac} = C_{m,c} \times 3,000 \times Y_{ac} \qquad (8)$$

The procedure for designing a polishing unit is similar to the one employed for designing a purification cartridge above. The polishing unit is assumed to be a short vertical cylinder made of ABS with slenderness ratio $r_{hd,pu} = 1.5$. The volume of activated carbon (V_{ac}) is calculated using Equation (3) by using the mass of activated carbon (W_{ac}) obtained from Equation (8) and the bulk density of the activated carbon (ρ_{ac}) from Table 2.

Similarly, the cost of activated carbon ($P_{t,ac}$) is calculated using Equation (4), using the mass of activated carbon (W_{ac}) from Equation (8) and the unit cost of activated carbon ($P_{u,ac}$) from Table 2. The volume ($V_{p,pu}$), amount ($W_{p,pu}$) and cost ($P_{t,p,pu}$) of plastic required are calculated using Equations (4)–(7), by using the volume of activated carbon (V_{ac}) from Equation (3), plastic density (ρ_p) and unit cost of plastic ($P_{u,p}$) from Table 2. The additional volume ($V_{addn,pu}$) for providing inlet, outlet as well as structural materials to hold the activated carbon are assumed to occupy an additional 100 cc. The weight, size and cost of the polishing unit are then calculated as the sum of those for activated carbon and plastic calculated above.

RESULTS

Batch disinfection studies were undertaken for each disinfectant in accordance with the procedure given above in the Materials and Methods section. Figure 1 summarizes the findings of the batch disinfection study, while Table 5 summarizes the minimum disinfectant concentrations (C_m) and contact times required to achieve 6 $\log_{10}$ reduction of
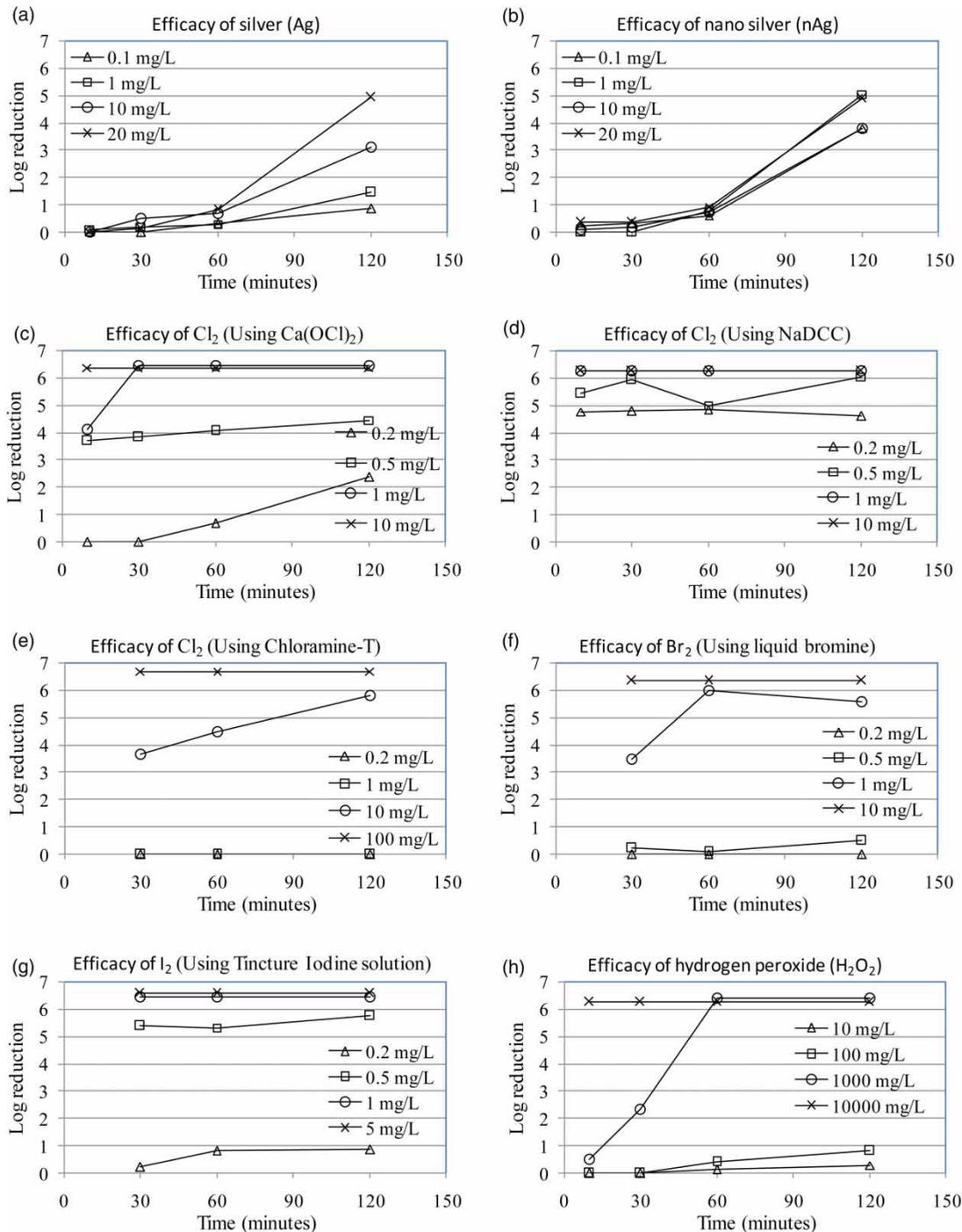

Figure 1 | Efficacy of disinfectants against *E. coli* ATCC 11229 (a) Ag (AgNO₃), (b) nAg solution, (c) Cl₂ (Ca(OCl)₂), (d) Cl₂ (NaDCC), (e) Cl₂ (Chloramine-T), (f) Br₂ (liquid bromine), (g) I₂ (tincture iodine) and (h) H₂O₂.

Table 5 | Minimum concentration and contact time required to achieve 6 $\log_{10}$ reduction against *E. coli* ATCC 11229

Active disinfectant	Source compound	Minimum concentration of active disinfectant (mg/L)	Source compound required to treat 1 L water (mg)	Contact time (minutes)
Ag^+	$AgNO_3$	10	15.75	180
nAg	Nano silver	1	1	180
Cl_2	$Ca(OCl)_2$ (Cl_2–33%)	1	3.03	30
Cl_2	NaDCC (Cl_2–62.5%)	1	1.6	10
Cl_2	Chloramine-T (Cl_2–25%)	10	40	120
Br_2	Liquid bromine	1	1	60
I_2	Tincture iodine (I_2–2% wt/vol)	1	48	30
H_2O_2	H_2O_2 (H_2O_2–30% wt/vol)	1,000	4,000	60

E. coli ATCC 11229 for all disinfectants considered in this study. The table also gives the minimum concentration of source chemical ($C_{m,sc}$) required to achieve the required concentration of active disinfectant in water calculated by using the formula given in Equation (1). Model purifiers were designed based on different disinfectants in terms of their replacement parts, i.e. purification cartridge and polishing unit, by following the procedure described above in the Materials and methods section. Table 6 summarizes the design parameters of the purification cartridges and polishing units of model purifiers in terms of their size, weight and cost. It also gives the selling price of the replacement parts of a model purifier by assuming a selling price to cost price ratio of 2.

The following sections describe the development of model purification cartridges based on the different disinfectants considered in this study.

Purifiers based on silver ions and nano silver

The efficacies of silver ions and nano silver against *E. coli* ATCC 11229 at different concentrations and contact times are summarized in Figure 1(a) and (b), respectively. As can be seen from Figure 1(a), concentrations of silver ions in the range of 0.1–20 mg/L show negligible reduction in bacterial count up to a 60 min contact period. Although the $\log_{10}$ reduction values increase steadily with contact time, up to 120 min no silver ion concentration in the range of 0.1–20 mg/L meets the USEPA requirement of a 6 $\log_{10}$ reduction. Similarly, as seen in Figure 1(b), no concentration of nano silver up to 20 mg/L achieves the desired reduction

during a 120 min contact period, although nano silver in general shows a higher $\log_{10}$ reduction as compared with silver ions. Considering the contact time dependence of silver, efficacy studies of silver ions and nano silver were extended to 3, 6 and 24 hours (see Figure 2(a) and (b)). At a 3 hour contact time, concentrations of 10 and 20 mg/L of silver ions show complete inactivation of *E. coli* whereas a 0.1 mg/L concentration of silver ions required a 24 hour contact time to achieve the same result. On the other hand, Figure 2(b) indicates that 1 mg/L concentration of nano silver was sufficient to completely inactivate *E. coli* over a 3 hour contact period. Hence the minimum concentrations of silver ions and nano silver required to meet USEPA requirements are 10 and 1 mg/L, respectively, and the minimum contact time required to achieve the inactivation is 3 hours. The above data were used to design model purifiers based on silver ions and nano silver by employing the procedures given above in the Materials and methods section. Since the concentrations of silver ions as well as nano silver required to achieve complete inactivation of *E. coli* are above the C_{MAC} value for silver in drinking water, it is expected that both these purifiers will require a polishing unit to remove the excess silver added to the water. Given that the $C_{m,c}$ value for silver ions is 10 times that for nano silver, it is expected that the cartridge as well as polishing unit for a purifier based on silver ions will be far more bulky than those for a purifier based on nano silver. This inference is also borne out in Table 6 where the size and cost of model purifiers is summarized. As seen from Table 6, the replacement parts for a purifier based on silver ions are expected to weigh 13.9 kg,

Table 6 │ Parameters of purifier replacements parts (purification cartridge and polishing unit) based on different disinfectants

Active disinfectant (Source compound/ solution)	Purification cartridge requirements			Polishing unit requirements			Purifier replacement part requirement			
	Amount (g) Chemical Plastic Total[a]	Size (cc) Chemical Plastic (dia.(cm)) Total[b]	Cost (US$) Chemical Plastic Total[c]	Amount (g) Polisher Plastic Total	Size (cc) Polisher Plastic (dia.(cm)) Total[d]	Cost (US$) Polisher Plastic Total	Total amount (g)	Total size (L)	Total cost (US$)	Selling price (US$)
Ag^+ ($AgNO_3$)	47.23 22.36 **112.76**	10.86 20.34 (2.88) **95.37**	59.6 0.09 **60.2**	13,044 833 **13,876**	20,380 792.94 (25.9) **21,273**	19.57 3.34 **22.91**	**13.9**	**21.4**	**83**	**166**
nAg (Nano silver powder)	3 16.94 **50.84**	1.67 16.13 (2.56) **68.7**	5.57 0.07 **6.14**	1,071 164 **1,235**	1,674 155.9 (11.46) **1,930**	1.61 0.12 **1.72**	**1.3**	**2**	**7.9**	**15.8**
Cl_2 ($Ca(OCl)_2$ (33%))	9.09 17.77 **59.59**	3.87 16.92 (2.62) **73.52**	0.004 0.071 **0.58**	1,154 172 **1,325**	1,803 163.34 (11.73) **2,066.23**	1.73 0.69 **2.42**	**1.4**	**2.1**	**3**	**6**
Cl_2 (NaDCC (62.5%))	4.8 17.75 **53.99**	5.05 16.9 (2.62) **73.4**	0.006 0.071 **0.58**	1,153 172 **1,325**	1,803 163 (11.73) **2,066**	1.73 0.69 **2.42**	**1.4**	**2.1**	**3**	**6**
Cl_2 (Chloramine-T (25%))	120 36.74 **222.74**	85.71 34.99 (3.8) **206.7**	1.08 0.15 **1.75**	11,538 768 **12,306**	18,029 731.12 (24.87) **18,860**	17.31 3.08 **20.39**	**12.5**	**19.1**	**22.1**	**44.2**
Br_2 (liquid bromine)	3 16.60 **49.9**	0.96 15.8 (2.53) **66.77**	0.017 0.066 **0.58**	546 108 **654**	852 103 (9.32) **1,055**	0.82 0.43 **1.25**	**0.7**	**1.1**	**1.8**	**3.6**
I_2 (Tincture iodine 2% wt/vol)	144 40.61 **214.61**	150 38.68 (3.99) **238.68**	0.818 0.163 **1.48**	375 87.14 **462.14**	585.94 82.99 (8.35) **768.93**	0.56 0.35 **0.91**	**0.7**	**1**	**2.4**	**4.8**
H_2O_2 (H_2O_2 30% wt/vol)	11,100 541 **11,672**	10,000 516 (14.73) **10,565**	5.44 2.17 **8.1**	– 	– 	– 	11.7	10.6	8.1	16.2

[a]Including weight of chemical, plastic, binder, additive and chemical dosing system.
[b]Including volume occupied by chemical, plastic, binder, additive, water connections and chemical dosing system.
[c]Including cost of chemical, plastic, binder, additive and chemical dosing system.
[d]Including volume occupied by polishing medium, plastic, water connections and accessories supporting the polishing medium.

occupy 21.4 L and costs US$166, whereas the replacement parts for a purifier based on nano silver are expected to weigh 1.3 kg, occupy 2 L and costs US$15.80.

Purifiers based on chlorine

Figures 1(c)–(e) summarizes the efficacy of chlorine against *E. coli* using the three chlorine releasing compounds: $Ca(OCl)_2$, NaDCC and Chloramine-T. As seen from Figures 1(c)–(e), when $Ca(OCl)_2$ was used as the chlorine source, complete inactivation of *E. coli* was observed within 30 min at a concentration of 1 mg/L of chlorine

while when NaDCC was used as the chlorine source, complete inactivation was achieved at the same concentration of chlorine albeit in only 10 min. On the other hand, a large concentration (10 mg/L of chlorine) of Chloramine-T was required to inactivate the test culture in 120 min. Correspondingly, it can be observed from Table 6 that the replacement parts of purifiers based on $Ca(OCl)_2$ and NaDCC are expected to be similar in weight, size and cost (i.e. 1.4 kg, 2.1 L and US$6), while those for a purifier based on Chloramine-T are expected to be far bulkier and expensive (weighing 12.5 kg, occupying 19.1 L and costing US$44.20).
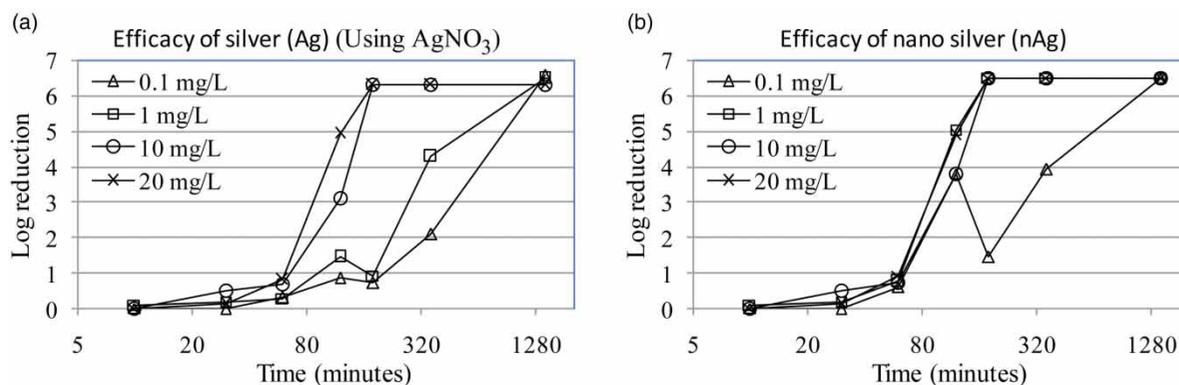
Figure 2 | Efficacy of disinfectants at longer contact times against *E. coli* ATCC 11229 (a) Ag (AgNO₃) and (b) nAg solution.

Purifier based on bromine

Figure 1(f) shows the efficacy of bromine against *E. coli*. A concentration of 1 mg/L of bromine is required to achieve a 6 $\log_{10}$ reduction over a 60 min period. At higher concentrations (10 mg/L), complete inactivation was observed within 10 min. However, given purifier size constraints, the lower concentration of 1 mg/L (albeit with a higher contact period) was considered for purifier calculations. As seen from Table 6, the replacement parts of a purifier based on bromine are expected to weigh 0.7 kg, occupy 1.1 L and cost US$3.60.

Purifier based on iodine

Figure 1(g) gives the efficacy of tincture iodine (in terms of free iodine) against *E. coli*. A concentration of 1 mg/L of iodine resulted in complete inactivation of the test culture during a 30 min contact period. Based on the above concentration, the replacement parts of a purifier using tincture iodine are expected to weigh 0.7 kg, occupy 1 L and cost US$4.80.

Purifier based on hydrogen peroxide

Figure 1(h) shows the efficacy of hydrogen peroxide against *E. coli*. As seen from Figure 1(h), even a 100 mg/L concentration of hydrogen peroxide achieved negligible inactivation over a 120 min contact period. Only at a very high concentration (1,000 mg/L), complete inactivation was observed after 60 min while 10,000 mg/L hydrogen peroxide gave complete

inactivation for all contact periods. Table 6 shows the replacement parts of hydrogen peroxide in terms of purification cartridge by using a $C_{m,c}$ value of 1,000 mg/L. The estimated size, weight and cost of a purification cartridge for treating 3,000 L using hydrogen peroxide are 10.6 L, 11.7 kg, and US$16.20, respectively. Even though the unit cost of hydrogen peroxide is expected to be low (US$0.49/kg), the volume of disinfectant needed to purify 3,000 L will make the resultant purifier very bulky and expensive.

DISCUSSION

Comparison of purifiers based on studied disinfectants

Purifiers based on silver ions and nano silver

Silver is known to be a clean disinfectant as it does not add taste, odor or color to treated water and more importantly does not produce any harmful byproducts after disinfection (Solsona & Méndez 2003). Silver and nano silver are generally employed in water purification applications in the form of solid powders, liquid solutions or by impregnating them into solid filtration media. In the current study, AgNO₃ and nano silver powder are considered as sources of silver ions and nano silver, respectively, and are assumed to be directly dosed into the water. We do not consider cases where either of these disinfectants is impregnated in a filtration medium since the basis of comparing disinfectants in the current study, the batch

disinfection test, assumes that the disinfectants are in direct contact with the water.

As discussed above under Results, the replacement parts of a model purifier based on silver ions will weigh 13.9 kg, occupy 21.4 L and cost US$166. Clearly, a purifier based on dosing of silver ions to water while still meeting USEPA log_{10} reduction requirements will not be a viable household purification solution. On the other hand, a purifier based on dosing of nano silver to water is expected to weigh 1.3 kg, occupy 2 L and costs US$15.80. Although the size and weight of such a purifier may be somewhat acceptable, the high cost of silver makes this solution an unviable option for most low-income households.

Recently, there has been an emergence of household water purification products based on nano silver. Examples include the Nano Silver Activated Carbon Filter (Aqua-Win 2012), the Nano Silver Ceramic Water Filter (Nagarajan & Jaiprakashnarain 2009) and Tata Swach® (Tata Swach 2012) which uses rice husk ash impregnated with nano silver as the filtration medium. Filtration media treated with high concentrations of nano silver, when brought in contact with contaminated water, can result in efficient inactivation of bacteria and viruses (Cioffi & Rai 2012; Mpenyana-Monyatsi *et al.* 2012). Since the total amount of nano silver needed to generate a high local silver concentration within the filtration media is not very large and since the silver, when efficiently bonded to the filtration media, leaches out only in trace quantities, a polishing unit may not be necessary in such purifiers. Thus, these purifiers are expected to be compact, efficient and cost effective. However, as mentioned above, purifiers based on silver impregnated purification media are beyond the scope of the current study.

Purifiers based on chlorine

Chlorine is the most commonly used disinfectant in water treatment plants. It can be applied for the inactivation of most microorganisms and it is relatively cheap. In the current study, three chlorine releasing compounds ($Ca(OCl)_2$, NaDCC and Chloramine-T) were tested for their feasibility of inclusion in low-cost POU water purifiers. As discussed above under Results, a purifier based on Chloramine-T will be bulky, expensive and infeasible. On the other hand, the replacement parts for purifiers based on $Ca(OCl)_2$ and NaDCC are expected to be fairly inexpensive (costing US$6), of acceptable size (2.1 L) and weight (1.4 kg), and are expected to be economically and ergonomically attractive to end users.

Purifier based on bromine

The replacement parts of a purifier based on bromine are expected to be even more compact (1.1 L) and cost effective (US$3.60) as compared with those based on chlorine. However, since bromine is a liquid at room temperature and vaporizes easily, it is expected that the construction of the bromine addition system in a purifier will be more complex as compared with purifiers using solid chemicals, such as $Ca(OCl)_2$ and NaDCC. The issues associated with dosing of liquid bromine can be avoided by using bromine-releasing compounds such as 1-bromo-3-chloro-5,5-dimethylhydantoin (BCDMH) (Moffa *et al.* 2006) and brominated *N*-halamine (Ahmed *et al.* 2011). The latter has been developed in the form of spherical porous beads which release bromine on coming in contact with water (Williams & Bridges 2010). Bromine releasing compounds can be enclosed in a purification cartridge without the need of a complex dosing mechanism. However, as with silver impregnated media, the evaluation of these media was beyond the scope of the current study.

Purifier based on iodine

The size and weight of a purifier based on tincture iodine are expected to be about the same as those for a purifier based on liquid bromine. The cost of the replacement parts of a purifier based on iodine (US$4.80) is expected to be somewhat higher than that for a purifier based on bromine (US$3.60) but is expected to be less than the cost of replacement parts for purifiers based on $Ca(OCl)_2$ (US$6) and NaDCC (US$6). There is some concern regarding continuous consumption of iodine by people who are iodine-sensitive, have over-active thyroids or are pregnant or nursing mothers (Backer & Hollowell 2000). This necessitates that the polishing unit employed in an iodine-based filter be robust and effective to remove all traces of iodine from the treated water before it is consumed by the end user (WHO 2011).

In the last few decades, iodinated resins, primarily in the form of tri-iodide or penta-iodide ion exchange resins, have been successfully deployed in POU water purifiers (Vasudevan & Tandon 2010). These resins are mostly used in granular form as a packed bed. When water passes through the bed, disinfection occurs when microorganisms are exposed to the high local concentration of iodine present in the vicinity of the resin. Since the current study is limited to the direct addition of disinfectant to water, it does not address purifiers which employ disinfection by the action of ion-exchange resins.

Purifier based on hydrogen peroxide

Hydrogen peroxide is used as a disinfectant in water treatment plants as well as in food and pharmaceutical industries (Pedahzur *et al.* 1997; Flores *et al.* 2012). However, as compared with other compounds such as halogens, ozone and UV, hydrogen peroxide is a mild disinfectant and hence is not used as a primary standalone disinfectant in treating drinking water (USEPA 2012b). Since the current study was limited to standalone disinfectants, complete inactivation of *E. coli* was observed only at the very high concentration (1,000 mg/L) of hydrogen peroxide. As seen above under the Results section, the replacement parts of a purifier based on hydrogen peroxide are bulky (10.6 L) and expensive (US\$16.20) hence, a purifier based solely on the action of hydrogen peroxide is not expected to be a feasible solution for low-cost household water purification.

Hydrogen peroxide exhibits synergistic action with other disinfectants such as silver and ozone as well as with exposure to UV rays and can thus form a part of an effective disinfection solution (Pedahzur *et al.* 1997). For example, a 'Sanosil Super 25' is a product based on the combination of H_2O_2 and silver, has been approved for use as a disinfectant for public water supply applications in the United Kingdom (DWI 2012).

Since the current study was limited to the action of a single disinfectant, the efficacy of hydrogen peroxide in conjunction with another disinfectant has not been evaluated. A future study may be extended to include the synergistic action of two or more disinfectants and evaluate purifiers based on such multi-disinfectant configurations.

Selection of disinfectant

As seen in Table 6, the cost of the replacement parts of purifiers based on the studied disinfectants in decreasing dollar value are: silver ions (US\$166), Cl_2 (using Chloramine-T as a source of Cl_2) (US\$44.20), hydrogen peroxide (US\$16.20), nano silver (US\$15.80), Cl_2 (using $Ca(OCl)_2$ and NaDCC as a source of Cl_2) (US\$6), I_2 (using tincture iodine) (US\$4.80) and Br_2 (US\$3.60). Similarly, the total size of replacement parts of purifiers based on the studied disinfectants in the decreasing order of occupied volume are: silver ions (21.4 L), Cl_2 (using Chloramine-T as a source of Cl_2) (19.1 L), hydrogen peroxide (10.6 L), Cl_2 (using NaDCC and $Ca(OCl)_2$ as a source of Cl_2) (2.1 L), nano silver (2 L), Br_2 (1.1 L) and I_2 (1 L).

Since the replacement parts of purifiers based on silver ions, nano silver, Chloramine-T and hydrogen peroxide are expensive and, with the exception of nano silver, are also very bulky, these may not be affordable nor convenient to the end user and hence may not form part of an acceptable low-cost household purification solution.

The replacement parts of a purifier based on liquid bromine, iodine (using tincture iodine), $Ca(OCl)_2$ and NaDCC are expected to be compact and cost effective and hence attractive to a large segment of the target population.

Among these four disinfectants, $Ca(OCl)_2$ is readily available and is regularly used for water purification applications. It is safe, easy to handle and inexpensive and hence is the disinfectant of choice of this limited study.

Study limitations

In the current study, we have assessed the effectiveness of commonly available disinfectants against the bacterial strain *E. coli* ATCC 11229. However, it may be noted that the effectiveness of disinfectants varies with the test strain and the type of microorganism (bacteria, viruses and protozoa). Hence, in order to get a realistic estimate of the comparative potency of disinfectants, the study needs to be extended to different groups of microorganisms and different strains within each group.

The current study assumes that the test disinfectants are in the form of a solid powder or concentrated liquid solution which is directly dosed in water. It ignores other methods of

bringing disinfectant in contact with microorganisms such as by using disinfectant impregnated filtration media and disinfectant releasing resins. A future study could include these methods to achieve a better comparison of the various options available for low-cost water purification.

The current study is also limited to the action of a single disinfectant. A further study could encompass the synergistic effect of combinations of disinfectants since some disinfectants show poor action in isolation while their performance improves significantly in the presence of other disinfectants. Such an extension to this study could provide valuable insights while designing purifiers incorporating multiple disinfectants.

CONCLUSIONS

The present study presents a comparison of commonly available disinfectants for their suitability of use in a gravity-driven, POU, low-cost, household water purifier. The disinfectants and corresponding disinfectant releasing compounds that have been studied are: silver ions (via $AgNO_3$), nano silver (using nano silver powder), chlorine (via $Ca(OCl)_2$, NaDCC and Chloramine-T), iodine (in the form of tincture iodine), bromine (as liquid bromine) and hydrogen peroxide (as a 30% hydrogen peroxide solution).

The study estimates that purifiers based on the addition of $AgNO_3$, nano silver, Chloramine-T and hydrogen peroxide to water are expected to be expensive and/or bulky and hence are not expected to be attractive to end users.

Purifiers based on liquid bromine, iodine, $Ca(OCl)_2$ and NaDCC are expected to be cost effective (US$3.60–6), of acceptable size (1–2 L) and weight (0.7–1.4 kg) and are thus expected to be ergonomically and economically attractive to end users. Among these disinfectants, $Ca(OCl)_2$ is widely available, easy to handle, inexpensive and safe, and hence it is the disinfectant of choice among the various disinfectants evaluated in this study.

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