Comparison of five point-of-use drinking water technologies using a specialized comparison framework

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ABSTRACT

Three novel and two commercially available low-cost point-of-use (PoU) water treatment technologies were comparatively evaluated using a specialized comparison framework targeted at them. The comparison results and specialized framework have been discussed. The PoU systems were evaluated principally in terms of performance, flow rate and cost per volume of water treated (quantitatively), ease of use, potential acceptability and material availability (qualitatively) with main focus on rural and suburban settings. The three novel systems assessed were developed in an ongoing research project aimed at developing a multibarrier low-cost PoU water treatment system. The comparative evaluation and analysis revealed that the commercially available systems may often produce water free of pathogens (with an apparent 100% removal for *Escherichia coli* and fecal coliforms) but may not be affordable for application to the poorest groups in much of the developing world. The novel systems, which were principally constructed from local materials, were more affordable, can supply relatively safe water and can be constructed by users with minimal training. Overall, bacterial removal effectiveness, ease of use, flow rate, material availability, cost and acceptability aspects of water were identified as key to potential adoption and sustainability of the evaluated low-cost PoU systems.

Key words | drinking water, low cost, novel technology, point-of-use, specialized comparison framework, water treatment

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INTRODUCTION

Provision of safe drinking water in developing countries can be best achieved by avoiding sophistication in technological design. Simplicity and reliability must be the keywords in the minds of designers and implementers of low-cost drinking water technologies (Ellis 1991). Although point-of-use (PoU) water treatment is not a replacement for formal provision of safe drinking water, it serves as a valuable interim measure for reducing the risk of waterborne diseases for about 660 million people with no access to improved supplies (WHO 2016). When the absence of fecal contamination is considered, the population in need of safer water increases to 1.9 billion (WHO 2016). According to the World Health Organization (WHO 2016), to realize health gains, PoU technologies must produce microbiologically safe drinking water and be correctly and consistently utilized. Furthermore, the systems must be able to produce aesthetically acceptable drinking water so that users do not opt for aesthetically better alternatives that may be unsafe (Hammer & Hammer 2012; CAWST 2017; WHO 2017a).

Safe drinking water is a significant problem in many poor communities due to widespread poverty and vulnerability levels. Boiling is often used in such settings and can be efficient at the elimination of waterborne pathogens. However, boiled water is not aesthetically acceptable to

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most people and is susceptible to recontamination due to unsafe handling and storage (Jagals *et al.* 1997, 2003; Potgieter *et al.* 2009; Genthe *et al.* 2013; WHO 2016; Supong *et al.* 2017; Kausley *et al.* 2018). It is time-consuming to boil and cool down the water, and the water to be boiled needs to be clear, often necessitating pretreatment. Additionally, boiling is energy-intensive and uses stoves and fuels, which lead to environmental impacts including contribution to climate change (WHO 2016). Therefore, developing and optimizing low-cost PoU systems that can efficiently remove pathogens from drinking water and improve acceptability aspects is warranted.

Although most PoU water treatment systems work primarily like centralized water treatment systems (Peter-Varbanets *et al.* 2009), quality, performance and sustainability vary significantly across these technologies. Many design guidelines and criteria exist for centralized water treatment systems (Kawamura 2000; Davis 2010), while PoU water treatment systems have varying guidelines and criteria. Most available low-cost systems may not be well designed and produced and may, therefore, be unable to give excellent sustainable performance. Comparative evaluation (quantitatively and qualitatively) of PoU systems is, therefore, necessary to ascertain the most apt system to use in a specific situation.

Three novel and two commercially available low-cost PoU water treatment systems were compared by means of a comparison framework developed specifically for them. The three novel systems assessed were developed by the authors in ongoing research aimed at developing and optimizing a low-cost multibarrier water treatment system. This specialized comparison framework has been developed based on the WHO Scheme for Evaluating PoU Water Treatment Technologies and reports by various water treatment researchers. Various performance criteria for low-cost PoU water treatment systems were comprehensively explored based on findings and recommendations by a number of authors (see Ellis 1991; McAllister 2005; Nath *et al.* 2006; Sobsey *et al.* 2008; Lantagne & Clasen 2009; Peter-Varbanets *et al.* 2009; CAWST 2011; Loo *et al.* 2012; Adeyemo *et al.* 2015; Stubbe *et al.* 2016; WHO 2016).

The three novel and two commercially available systems were assessed both quantitatively and qualitatively using the developed comparison framework. Bacterial diseases, e.g. acute gastroenteritis, cholera, diarrhea, dysentery, typhoid, etc. cause far more health problems than viruses or chemicals as a result of drinking untreated water (WHO/UNICEF 2004; McAllister 2005). Therefore, bacterial removal was afforded high priority in the evaluation criteria. Special attention was given to the application of the comparative framework in evaluating low-cost filtration technologies. This is because the evaluated PoU technologies were mainly filtration-based.

The two evaluated commercial PoU systems were the gift of water filter system (GWS) and drip filter system (DFS) manufactured in the USA and South Africa, respectively, and previously researched by the authors (Siwila & Brink 2018a). The three novel systems evaluated in this study were: (i) the modified intermittently operated slow sand filtration system (ISSFGeoGAC) incorporating geotextile and granular activated carbon (GAC) for removal of bacteria, particles, color, taste, odor and selected heavy metals (Siwila & Brink 2018b), (ii) the eight-layer four-pot sequential bidim filtration system using bidim geotextile (BidimSEQFIL) for removal of bacteria and particles (Siwila & Brink 2018c), and (iii) the wood filtration system combined with GAC (WFSGAC) for removal of bacteria, color, taste, odor, particles and heavy metals (Siwila & Brink 2018d). These filtration technologies were developed and tested as a contribution to research on affordable PoU water treatment systems appropriate to poor communities producing water with a high degree of acceptability.

It is hoped that the developed comparative framework presented here will support the WHO PoU evaluation scheme and promote the adoption of novel PoU technologies. It is further envisaged that such an exercise may bring out new research insights. That is, researchers and implementers may be encouraged to carry out studies aimed at optimizing novel technologies, e.g. in terms of pollutants of interest, ease of use, maintenance requirements, etc.

For instance, based on a preliminary evaluation using various published literature (Graham & Mbwette 1987; Muhammad *et al.* 1996; Manz 2004; Stauber *et al.* 2006; Jenkins *et al.* 2009; Binnie & Kimber 2013; NE-WTTAC 2014; CAWST & SPC 2017), the first of the three novel technologies being evaluated was developed. Although there is still room for improvement, laboratory tests by Siwila & Brink (2018b) showed that the novel technology is expected to perform better than the traditional ISSF systems.

Meanwhile, the initial literature review showed that ISSF systems, particularly the institutional scale (CAWST & SPC 2017), still need further improvement in terms of cleaning frequency and removal of other contaminants such as metals, color, taste and odor. GAC was, therefore, added to improve contaminant removal (Siwila & Brink 2018b). Geotextile filter mats were placed on the sand surface to minimize the cleaning frequency whereby the filter mats are to be cleaned instead of the traditional sand removal scraping or 'swirl and dump' (surface agitation and stirring) cleaning techniques (CAWST 2011; Singer *et al.* 2017). The traditional cleaning methods are somewhat tedious and tend to render the technology less acceptable to users. This is further worsened by inconsistencies in producing water free of color, taste and odor as well as significant reduction in bacterial removals after cleaning (Singer *et al.* 2017).

Therefore, in this study, a specialized comparison framework for low-cost PoU water treatment systems was developed and used to evaluate five low-cost PoU systems. Although particular emphasis was placed on the elimination of bacteria, improvement of the acceptability aspects of water was also given high priority so that users do not opt for water that seems more acceptable but is contaminated.

MATERIALS AND METHODS

Design considerations and evaluation criteria

A thorough review of published literature was done and showed that there is currently no documented standard on design and suitability of low-cost PoU systems based on quantitative specifications. The quality of many low-cost PoU technologies relies primarily on the materials used and the fabricator's skill. There is a gray area in which scientific and engineering judgement must be employed to determine the level to which a PoU technology is suitable. Studies and field experiences by various authors on various PoU water treatment technologies showed suggested guidelines and criteria (see McAllister 2005; Nath *et al.* 2006; Peter-Varbanets *et al.* 2009; Sobsey *et al.* 2008; Loo *et al.* 2012; WHO 2016). Table 1a shows that contaminant removal performance, ease of use, social acceptability, cost, flow rate, implementation potential (i.e. training, technical personnel for installation and repairs, availability of spare parts, energy requirements, chemical requirements, etc.), pore size, brushing and removing silver from ceramic candles are among the main criteria which affect effectiveness as proposed by various authors.

Principally, the table was generated qualitatively through content and text analysis of the referenced literature. The extracted criteria were then logically arranged. Thereafter, the criteria for the specialized comparison framework were developed (Table 1b). Definitions of the comparison framework evaluation criteria, some of which are adapted from Table 1 references, were then provided (Table 2).

PoU technology suggested guidelines and evaluation criteria

Various PoU technology evaluation criteria have been suggested by different authors as summarized in Table 1. For example, CAWST (2011) noted five main criteria for evaluating PoU water treatment technologies, namely: (1) effectiveness (the quality and quantity of the water that can be treated), (2) appropriateness (availability, time for treatment, work involved and estimated life span of the technology), (3) acceptability (the ease of use and the acceptability of the users or user perception and buy-in), (4) cost to user (capital/initial costs, maintenance and ongoing costs), and (5) implementation (what is required to get the technology into people's homes, e.g. training for users to properly use the technology, monitoring required for the technology, additional support, etc.). McAllister (2005) proposed the following guidelines in order to achieve sustainable low-cost PoU technologies: (1) little or no use of nonrenewable energy during the production or technology use, (2) minimal environmental impact during the production or technology use, (3) selected materials should be readily available and/or easy to manufacture, (4) manufacturing processes should be safe and efficient, and (5) technology should regard cultural principles, practices, or customs. Published criteria, therefore, vary in terms of content and importance given to different elements.

Most suggested criteria were scattered with no provided definitions and systematic guidance for technology evaluation. In addition, most of the proposed criteria were generalized

Table 1 | (a) Summary of key PoU technology characteristics and evaluation criteria as extracted from content and text analysis of various literature and (b) the framework evaluation criteria

(a) Extracted/suggested PoU water treatment technology evaluation criteria										**Reference/Source**
Investment cost US$	Operational cost US$	Performance	Ease of use	Maintenance	Sustainability	Energy requirement	Social acceptability			Peter-Varbanets *et al.* (2009)
Cost (US$)	Environmental impact	Performance	Ease of use and deployment	Maintenance	Life span	Energy requirement	Social acceptability	Water production rate (L/h)	Supply chain	Loo *et al.* (2012)
Manufacturing cost US$	Environmental impact	Pollutant removal	Locally made	Manufacturing time	Material availability	Filter pore size (microns)	Socially acceptable	Capacity (liters/h)		McAllister (2005)
Capital/initial costs US$	Ongoing costs US$	Pollutant removal	Ease of use	Maintenance	Estimated life span	Locally made	Socially acceptable	Quantity treated (L/h)	Training needs	CAWST (2011)
Cost (US$)		Pathogen removal		Generally, 'free-standing'	Material availability	Local availability	Appropriate	Quantity treated	Training needs	WHO (2016)
Capital costs (US$)	Running costs (US$)	Pollutant removal	Ease of operation	Storage ability	Robustness (durability)	Sustainability and maintenance	Social acceptance	Quantity treated	Training needs	Adeyemo *et al.* (2015)
Price (US$)	Retail price (US$)	Effectiveness	Price/m^3	Locally produced	Life span	Maintenance cost	Acceptability	Flow rate (L/h)	Training and monitoring needs	Stubbe *et al.* (2016)
Cost (US$)	Running costs (US$)	Performance	Ease of use	Environmental impact	Availability	Energy requirement	Improves taste	Time efficient	Replicable	Sharma & Sood (2016)
Cost (US$)	Running costs (US$)	Performance	Ease of use	Public health hazard	Local materials	Energy requirement			Technical assistance	Ellis (1991)
Cost (US$)	Running costs (US$)	Performance	Ease of use	Maintenance	Sustainability	Treatment robustness	Health impacts	Time treating water	Supply chain	Sobsey *et al.* (2008)
Cost (US$)	Running costs (US$)	Performance	Ease of use	Maintenance	Local availability	Life span	User acceptability	Flow rate (L/h)	Supply chain	Lantagne & Clasen (2009)
Cost (US$)	Running costs (US$)	Performance	Ease of use	Maintenance	Availability	Energy requirement	Practicality	Flow rate (L/h)	Supply chain	Nath *et al.* (2006)
Cost (US$)	Running costs (US$)	Performance	Ease of use	Maintenance	Sustainability	Energy requirement	Social acceptability	Volume treated	Supply chain	Mac Mahon & Gill (2018)

(b) Developed framework evaluation criteria: listed from most critical to least critical (left to right)

Performance	Ease of use	Water throughput	Acceptability potential	Energy requirement	Cost	Ease of deployment	Durability	Maintenance	Environmental impact	Supply chain

Table 2 | Score definitions with respect to each of the PoU-specialized comparison framework's evaluation criteria[a]

	Meaning of scores used in the comparison				
Evaluation criteria	**1**	**2**	**3**	**4**	**5**
Performance	Fair pathogen removal (1–2 LRVs); treatment efficiency affected by variations in raw water quality; cannot remove color, taste, odor and turbidity	Fair pathogen removal (1–2 LRVs) ; treatment efficiency affected by variations in raw water quality; can remove color, taste, odor and turbidity	Good pathogen (2–3 LRVs) removal; treatment efficiency not affected by variations in raw water quality; cannot remove color, taste, odor and turbidity	Excellent (4–5 LRVs) pathogen removal; treatment efficiency not affected by variations in raw water quality; can remove color, taste, odor, turbidity	Exceptional pathogen removal (6–8 LRVs); treatment efficiency not affected by variations in raw water quality; can remove color, taste, odor and turbidity and various chemical contaminants
Ease of use	Needs very skilled operators; complex system design; difficult to operate	Needs skilled operators and/or operation is laborious	Needs some form of user training; relatively easy to operate	Needs very little user training; very easy to operate	Virtually no user training needed; very easy to operate
Water throughput	Very low flow rate (<7.5 L/d)	Low flow rate (<15 L/d);	Flow rate is fair (>15 L/d)	High flow rate; can meet drinking water needs of a household, small community or institution	High flow rate; can meet drinking water needs of a large community or institution
Acceptability potential	No improvement in appearance, smell, and taste of the treated water; difficult to use	No improvement in appearance of the treated water; treated water has acceptable taste and smell; difficult to use	Improved appearance in the treated water; acceptable taste and smell; relatively easy to use	Improved appearance in the treated water; acceptable taste and smell; easy to use, may not be user-friendly to everyone	Improved appearance in the treated water; acceptable taste and smell; very easy to use, acceptable among many user groups
Energy requirement	Substantial quantities of energy required and does not run on renewable energy	Substantial quantities of energy required; can run on renewable energy	Minimal energy requirement or uses tap pressure	Tap pressure or gravity fed; no electricity needed	Gravity-driven; no dependence on utilities
Cost	>US$10/m^3	US$5/m^3–US$10/m^3	US$1/m^3–US$5/m^3	<US$1/m^3	One-off cost needed (0–50 US$/unit); no operational costs required
Ease of deployment	Too heavy or delicate to be transported; has to be constructed or assembled at the PoU	Heavy or delicate; major parts require expert assembly at the PoU	Heavy but not delicate; system set up at the PoU is relatively easy	Light, small and not delicate; very easy to assemble; can be transported in large numbers	Light, small and not delicate; ready to use; can be transported in large numbers
Durability	Easily breakable and requires frequent repairs	Cannot break easily but requires frequent repairs	Made of durable materials; repairs are often needed	Made of durable materials and requires periodical repairs	Made of durable materials and requires virtually no repairs
Maintenance	Maintenance is complex, frequently performed and takes a lot of time	Maintenance is complex, frequently performed but takes little time	Maintenance is easy, takes little time but is performed frequently	Maintenance is easy, takes little time and performed periodically	Virtually no need for maintenance

Environmental impact	Can pollute or cause damage to the environment, e.g. can release greenhouse gases; uses fossil fuels	Little pollution or damage to the environment; uses fossil fuels and nonrenewable materials	No pollution or damage to the environment; uses gravity or renewable energy; partly made of nonrenewable materials	No pollution or damage to the environment; mainly made of renewable materials and gravity fed	No damage or pollution to the environment; made entirely of renewable materials and gravity fed
Supply chain	Nonstop supply of consumables needed whose stocks are only obtainable from certain dealers	Nonstop supply of consumables needed, but consumables can be easily obtained	Needs timely replacement of some parts obtainable from certain dealers only	Needs timely replacement of some parts; spare parts can be easily obtained	Everything is locally available or easily obtainable

LRVs, log removal values (mainly targeted at bacterial removal).

[a] Key references for this table are those listed in Table 1.

not necessarily focused on low-cost systems. The criteria adapted and proposed in this study were chosen to be suited specifically to low-cost systems.

Therefore, this study is aimed towards the provision of necessary detailed guidance (Figure 1), definitions (Table 2), a background compilation of criteria suggestions by various authors (Table 1), quantitative comparisons (Table 4), qualitative comparisons (Table 5) and a decision matrix (Table 6) for low-cost PoU technology analysis and assessments. In addition, the criteria for the developed comparison framework emphasize factors such as system durability and acceptability potential of treated water. Product durability may promote the adoption of a novel technology by users. Drinking water of high acceptability will certainly prevent users from opting for more appealing water that may not be safe (CAWST 2017; WHO 2017a). Although acceptability aspects of water may have little health significance, their presence could reflect treatment malfunction and the likely presence of other contaminants (WHO 2017a). Some technologies, such as those based on chemical treatment, may produce water which is virtually free of pathogens but has a bitter taste or color. Such types of water may in some cases not be acceptable to various consumers, minimizing its health impacts. This can also be supported by published work from various authors who have done PoU water- and health-related work in South Africa and other regions of the world (e.g. Jagals *et al.* 2003; Ashbolt 2004; Gundry *et al.* 2004; Potgieter 2007; Sobsey *et al.* 2008; Potgieter *et al.* 2009; Genthe *et al.* 2013; Momba *et al.* 2013; Curry *et al.* 2015; Singer *et al.* 2017), where social and aesthetic acceptability were investigated and found to be vital to the acceptance and sustainability of various low-cost PoU systems. For instance, Potgieter *et al.* (2009) indicated that people associated chlorine smell and taste of water with cholera outbreaks as it was recommended to add bleach to their drinking water after boiling during cholera outbreaks in rural areas of South Africa's Limpopo Province. That is, water that tasted of chlorine was only consumed during the outbreak, and rarely afterwards even where people suspected that their water quality was not good.

The WHO PoU evaluation scheme

The WHO evaluation scheme for PoU drinking water technologies focuses primarily on reference pathogens

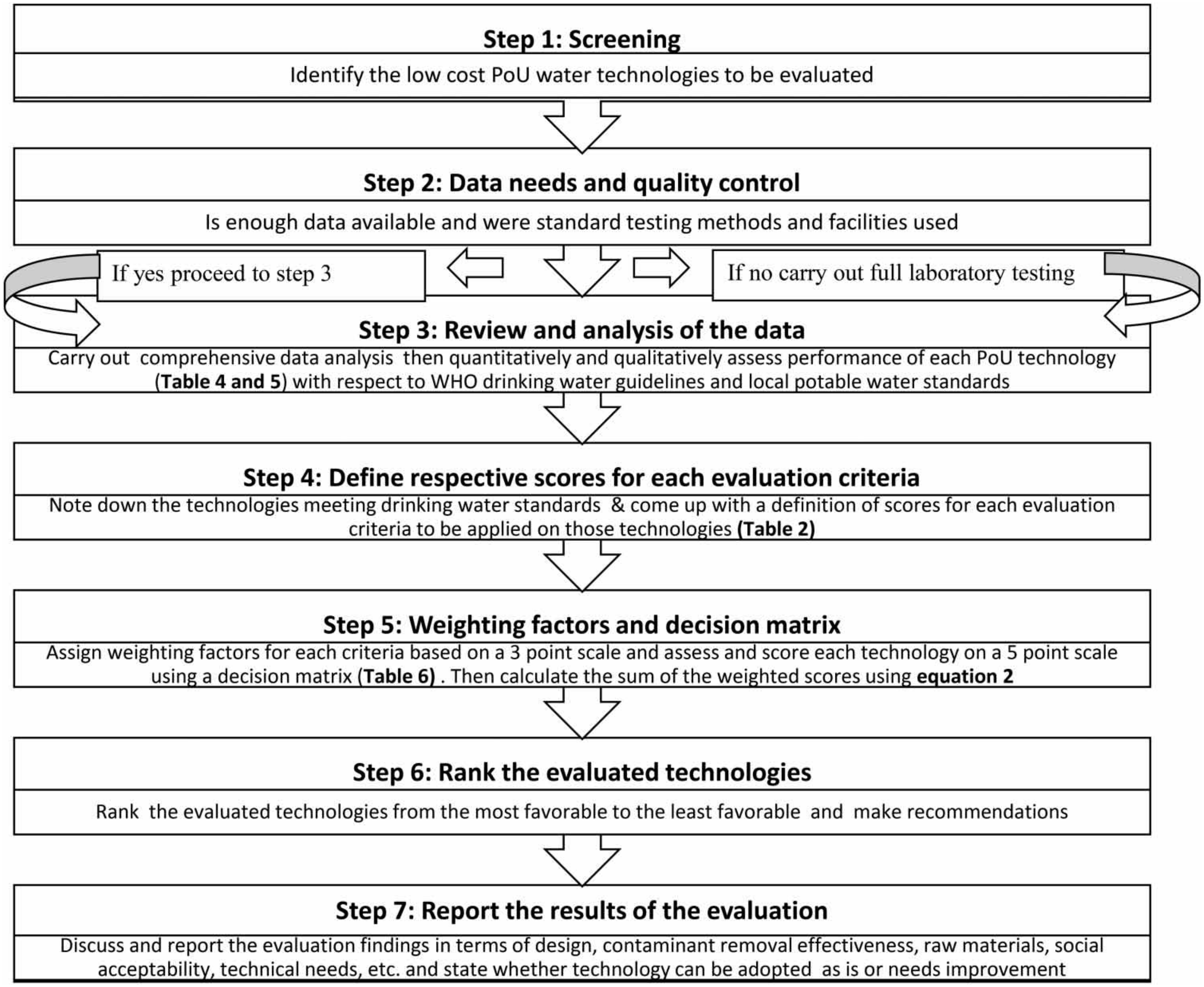

Figure 1 | An overview of the specialized comparison framework evaluation procedure.

(Table 3). According to WHO (2016), priority PoU technologies selected for evaluation are those that are: (1) low cost; (2) appropriate for low-income communities; (3) generally 'free-standing' and do not require being plumbed in; and (4) only treat sufficient water to serve a small number of users a day, for households or small settings such as schools, health care centers, etc. The Water, Sanitation, Hygiene and Health Unit of WHO coordinates the scheme. The unit (WHO 2016) (1) reviews and assigns testing laboratories, (2) develops testing procedures and report formats, (3) manages PoU technology testing, (4) reviews test results and (5) conveys PoU evaluations results to Member States.

Suggested test organisms for the specialized comparison framework

Although the WHO evaluation scheme recommends testing three classes of pathogens in water (bacteria, virus and protozoa) for microbial safety (Table 3), only fecal indicator bacteria (*Escherichia coli* and fecal coliforms) were used in this study. *E. coli* and to some degree fecal coliforms are accepted to best meet the criteria for an ideal fecal contamination indicator (Ashbolt *et al.* 2001; Cabral 2010; Fewtrell & Bartram 2013). The presence of these signals indicates that pathogens are present, and the water can, therefore, be regarded as being unsafe.

Table 3 | Test organisms of the WHO Scheme and recommended microbiological performance criteria (WHO 2016)

			Recommended targets for microbiological reduction by PoU water treatment systems (LRV)		
Pathogen class	**Organism**	**Key considerations in PoU water technology evaluation**	**Comprehensive protection: very high pathogen removal**	**Comprehensive protection: high pathogen removal**	**Targeted protection**
Bacteria	*Escherichia coli*	• Well-characterized fecal indicator organism; frequently found in raw water sources • Most sensitive organism to disinfection	≥4	≥2	Achieves 'protective' target for at least two classes of pathogens
Virus	*MS2* and *PhiX174* (human viral surrogates)	• Widely used surrogates for human viruses • Broad variety of traits and subsequent variations in sensitivity to water treatment • Well-characterized susceptibility to various disinfectants	≥5	≥3	
Protozoa	*Cryptosporidium parvum* oocysts	• Relatively resistant to chemical disinfectants but sensitive to UV irradiation • Readily removed by physical processes, e.g. filtration	≥4	≥2	

1 log removal value (LRV) = 90%; 2 LRV = 99%; 3 LRV = 99.9%, 4 LRV = 99.99%; 5 LRV = 99.999%.

Moreover, protozoa are readily removed by filtration technologies such as those being evaluated (DrinC 2017; Gift of Water Inc. 2017) and viruses can be inactivated by most disinfectants (WHO 2016). In addition, viruses have been associated with fewer health indices or lower illness rates to date than bacteria (USEPA 1987; Sobsey 1989; Ashbolt *et al.* 2001; WHO/UNICEF 2004; McAllister 2005; WHO 2011; Bartram & Hunter 2015). However, making use of surrogates (*bacteriophages* for viruses, *Cryptosporidium* or *Giardia* species for protozoan parasites and *E. coli* or *Enterococcus* for bacteria) is still recommended for future application of the developed framework. This is in order to be in harmony with the WHO evaluation scheme which suggests the use of three classes of pathogens. This can be done in places where testing for the mentioned surrogates is relatively simple, available and cost-effective.

The specialized comparison framework vs. the WHO PoU evaluation scheme

As stated above, the WHO evaluation scheme requires testing for three classes of pathogens (bacteria, viruses and protozoa) using challenge test waters. This is more ideal but may not be feasible in many poor communities especially in rural and remote areas. The framework developed in this study recommends testing for indicator bacteria (*E. coli* and/or fecal coliforms) while other pathogens can be tested if resources allow. In addition, the WHO evaluation scheme procedure mainly stresses evaluating pathogen removal performance, while the developed comparison framework emphasizes assessing both bacterial removal performance and the acceptability aspects of water. Furthermore, the WHO evaluation scheme has not distinctively provided defined scores and a corresponding decision matrix for possible comparisons such as included in the specialized comparison framework. In addition, the WHO evaluation scheme is mainly suited to PoU technologies that can primarily eliminate all pathogens. These include membrane ultrafiltration, flocculation–disinfection, UV disinfection, chemical disinfection and solar disinfection (WHO 2016), most of which are relatively expensive to poor communities. In resource-limited situations, water that is of reasonable quality (0–10 CFU/100 ml *E. coli* levels) and

Table 4 | Quantitative comparison of the PoU water treatment systems

PoU technology	*E. coli* removal (%)	Fecal coliforms removal (%)	Turbidity removal (%)	TSS removal (%)	Heavy metal removal (%)					Max. flow rate (L/day)		Cost (US$)		Reference
					As	Cd	Pb	Fe	Mn	Max	Min	Capital	Operation (per m^3)	
ISSFGeoGAC	96	96	89–100	87–100	30	94	63	71	94	242	152	24	0	Siwila & Brink (2018b)
BidimSEQFIL	99.9	99.9	95	95	d.n.a	d.n.a	d.n.a	d.n.a	d.n.a	4416	n.t	1.76/m^2	0	Siwila & Brink (2018c)
WFSGAC	100	100	100	100	65	74	94	99	n.d	7.6	3.6	<0.5	<0.1	Siwila & Brink (2018d)
GWS	100	100	61–97	66–99	d.n.a	d.n.a	d.n.a	d.n.a	d.n.a	1123	480	25	1.25	Gift of Water Inc. (2017) and Siwila & Brink (2018a)
DFS	100	100	82–99	83–100	99	d.n.a	98	96	d.n.a	318	82	44	0	DrinC (2017) and Siwila & Brink (2018a)

n.d = not detected; n.t = not tested; d.n.a = data not available; 0 = no running costs.

relatively safe (11–100 CFU/100 ml *E. coli* levels) may be consumed as is (WHO 1997; Harvey 2007; CAWST 2013). Additional solar and/or chemical disinfection according to WHO guidelines for drinking water quality (WHO 2017b) is, however, still recommended to ensure the complete elimination of pathogens.

Comparison framework evaluation procedure

Highlighted in Figure 1 are the key steps of the specialized comparison framework evaluation procedure. Screening is done to identify the low-cost PoU water technologies to be evaluated in **Step 1**. This is essentially based on availability, user needs and engineer/implementer interests. Data needs are defined, and the quality of available data is assessed (**Step 2**). In **Step 3**, if data are unavailable then adequate testing of the novel technology should be done. If data are available, comprehensive review and analysis should be done followed by quantitative and qualitative performance assessment of each PoU technology (Tables 4 and 5). WHO drinking water guidelines and local potable water standards can be used in assessing the safety of water. In **Step 4**, technologies meeting potable water standards are noted and respective scores for each evaluation criteria are defined (Table 2). The criteria in Table 2 have been ranked in order of most critical to least critical.

In **Step 5**, a decision matrix is generated. Criteria scores are then categorized as being least favorable (bad) to most favorable (excellent) (Tables 5 and 6). Weighting factors are assigned to each criteria based on a three-point scale (Table 6). Each technology is then assessed and scored using a five-point scale (Table 6). The sum of the unweighted and weighted scores of each technology is then calculated using Equations (1) and (2) respectively. In **Step 6**, the technologies are comparatively ranked and compared from the most favorable to the least favorable using the weighted scores (Figure 6). **Step 7** essentially involves discussing and reporting the evaluation findings in terms of features such as design, contaminant removal effectiveness, raw material availability, social acceptability, technical needs, etc. Conclusions and recommendations are then made on whether the novel low-cost technology can be adopted

Table 5 | Qualitative comparison of the PoU water treatment systems

			Improvement of acceptability aspects				Material availability		
PoU technology	**Locally made**	**Ease of use**	**Turbidity**	**Colour**	**Taste**	**Smell**	**Urban areas**	**Rural areas**	**Environmental impact**
ISSFGeoGAC	Yes	3	5	5	5	5	4	3	3
BidimSEQFIL	Yes	2	5	3	4	3	4	2	4
WFSGAC	Yes	2	5	5	5	5	3	5	3
GWS	No	3	4	3	4	4	3	2	3
DFS	Yes	4	4	4	4	5	3	2	3

5 = excellent; 4 = good; 3 = average; 2 = poor; 1 = bad.

as it is or needs further improvement.

$$\delta_{uw} = \gamma_1 + \gamma_2 + \gamma_3 + \ldots + \gamma_n = \sum_{k=1}^{n} \gamma_k; \quad for\ k = 1, 2, \ldots\ldots, n \tag{1}$$

$$\delta_w = \beta_1\gamma_1 + \beta_2\gamma_2 + \beta_3\gamma_3 + \ldots + \beta_n\,\gamma_n = \sum_{k=1}^{n} \beta_k\gamma_k; \quad for\ k = 1, 2, \ldots\ldots, n \tag{2}$$

where δuw = sum of unweighted criteria scores; δw = sum of weighted scores; β = weighting factor; $\gamma 1 \ldots \gamma n$ = respective criteria scores; γk = score for the kth criteria; k indexes the n-criteria.

RESULTS AND DISCUSSION

Description and analysis of the five point-of-use technologies

The individual PoU technologies which were evaluated are briefly discussed below in terms of system description, application, advantages, disadvantages, etc. The qualitative and quantitative comparative performance for each system is presented in Tables 4 and 5. For more information on each system, the reader is referred to the respective cited work.

Modified intermittently operated slow sand filtration system

Developed by the authors, ISSFGeoGAC (Figure 2) is a novel gravity-driven intermittently operated slow sand filter incorporating geotextile and GAC for removal of bacteria, particles, color, taste, odor and selected heavy metals (Siwila & Brink 2018b). Its gravity head is 10 cm. It uses fine sand of effective size (ES) = 0.16 mm and uniformity coefficient (UC) = 2.0 and depth of 14.5 cm. The coarse sand size is of ES = 0.30 mm and UC = 2.4 with a depth of 14.5 cm. The GAC is of 10 cm depth and gravel layer depth is 9 cm. During filtration, particles and pathogens are physically and biologically removed from water as it passes through the system. The key contaminant removal mechanisms which take place in the biolayer and within the filter body are trapping, predation, absorption and natural bacterial death (CAWST 2010). Filter mats have been included to serve as a pretreatment to enhance performance and reduce clogging.

The geotextile fabric also concentrates the major part of water purification within the mats and therefore less purification action happens within the sand (Graham & Mbwette 1987). The filter mats are also expected to extend filter run times and offer easy filter cleaning by removal and washing of the fabric alone as opposed to 'scraping' or 'swirl and dump' in ordinary ISSF systems (Graham & Mbwette 1987). GAC has been included to supplement adsorption capacity and allow removal of other contaminants, e.g., arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), iron (Fe) and manganese (Mn) (Siwila & Brink 2018b). The system has been designed to include the mentioned materials, to enhance performance so that the system is expected to improve water quality with respect to bacteria, acceptability aspects (turbidity, color, taste and odor) and the said heavy metals, thus increasing health benefits and filter run times, while minimizing the cleaning frequency.

Table 6 | Comparison framework decision matrix

Criteria scores for comparison of the PoU water treatment technologies

	Performance	Ease of use	Water throughput	Acceptability potential	Energy requirement	Cost	Ease of deployment	Durability	Maintenance	Environmental impact	Supply chain	Comparative score	
Weighting factor⇨	3	3	2	3	3	2	2	2	2	1	1	Unweighted	Weighted
ISSFGeoGAC	5	3	4	4	5	3	3	4	4	3	4	42	94
BidimSEQFIL	3	2	4	2	5	4	4	4	3	4	4	39	82
WFSGAC	5	2	2	2	5	4	2	3	3	3	3	34	76
GWS	5	3	4	3	5	3	4	4	3	3	3	40	90
DFS	5	4	3	4	5	3	4	3	3	3	3	40	92

Evaluation criteria: 5 = excellent; 4 = good; 3 = average; 2 = poor; 1 = bad. Weighting factors: 3 = most critical; 2 = moderately critical; 1 = least critical.

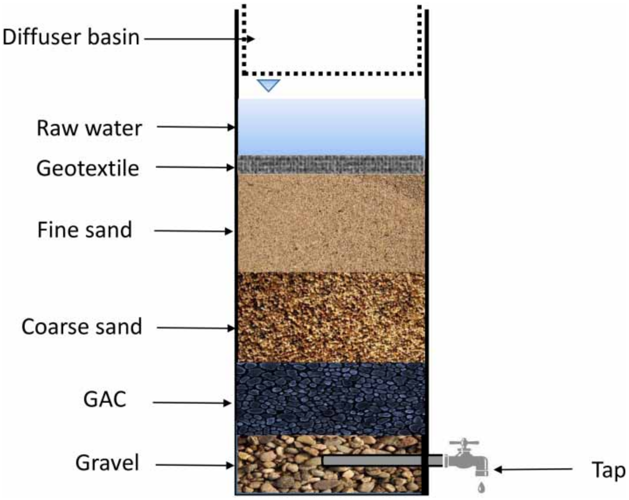

Figure 2 | Schematic diagram of the ISSFGeoGAC filter system.

Advantages

(i) Easy to use, (ii) enhanced acceptability of treated water, (iii) can be produced locally, (iv) added benefit of removing heavy metals, (v) extended filter run times, (vi) reduced cleaning frequency and subsequent biolayer disturbance, (vii) uses local and easily accessible materials, (viii) low cost, (ix) gravity-driven, (x) it is replicable.

Limitations

(i) No protection against recontamination except if treated water is safely stored, (ii) periodical replacement of GAC attracts some running costs, (iii) relatively heavy for distribution.

Sequential bidim filtration system (BidimSEQFIL)

The sequential bidim filtration system (Figure 3) is an optimized fabric filtration method developed by the authors for low-cost water treatment (Siwila & Brink 2018c). The optimized eight-layer four-pot sequential filtration method using Bidim A8 can produce very clear drinking water of reasonable quality (0–10 CFU/100 ml *E. coli* levels) that may be consumed as is (WHO 1997; Harvey 2007; CAWST 2013; Siwila & Brink 2018c). Bidim A8 has an average pore size of <75 μm (Kaytech Engineering 2018) and a layer thickness of about 6 mm (Siwila & Brink 2018c). The fabric costs about 1.76 US$/m^2. It is a nonwoven, engineered fabric,

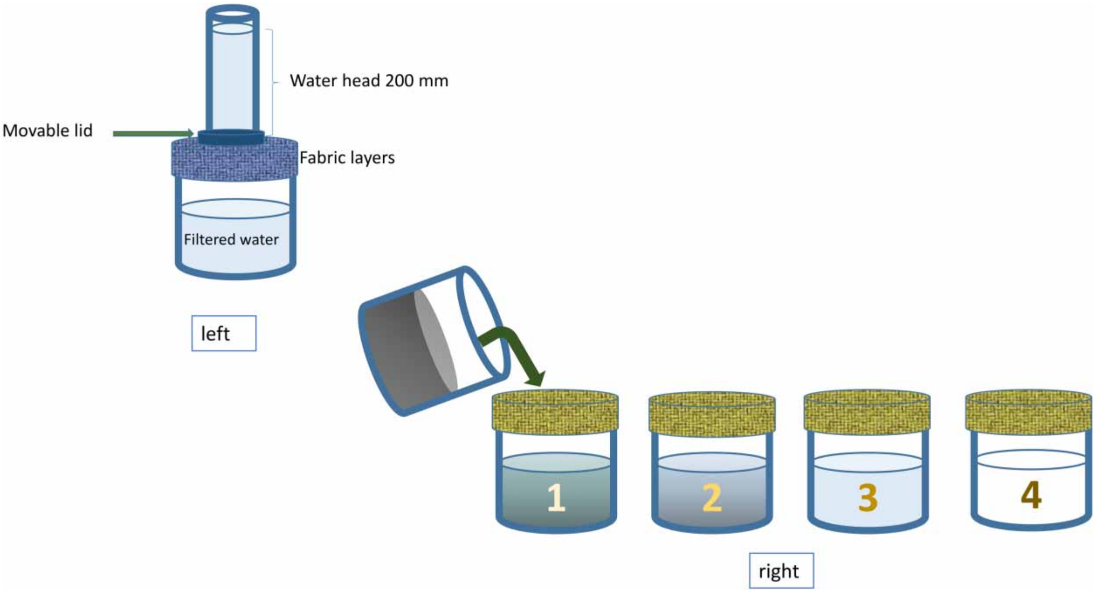

Figure 3 | General filtration setup with movable lid for flow rate measurement (left); four-pot sequential filtration (right).

continuous filament, needle punched 'food grade' geotextile manufactured by Kaytech Engineering, South Africa. It is normally applied in hydraulic applications such as for erosion control, filtration and drainage, hydraulic and retaining structures, water and waste containment and as a turbidity curtain during bay constructions (Kaytech Engineering 2018). As water is filtered through the first to fourth pot set (Figure 3), impurities (bacteria, turbidity and suspended solids) are removed. Clean water is stored and obtained from the fourth pot. When pores become clogged, the bidim fabrics need to be washed. The fabric can be easily removed and washed to remove trapped dirt, thereby ensuring adequate flow rates.

Advantages

Bidim has comparative advantages for drinking water treatment over cloth fabrics as it is stronger and can be reused more often with fewer cleaning needs. BidimSEQFIL can substantially remove indicator bacteria up to 3 LRV. This is much better than both ordinary fabric filtration and three-pot settling methods. The fabric is easy to wash without significant fabric loosening by normal hand-washing. It can be disinfected in ordinary utility ovens at around 100–200 °C and is structurally stable up to 200 °C (Kaytech Engineering 2018).

Limitations

(i) Relatively laborious compared to other filtration methods, (ii) periodical washing of the bidim fabric, (iii) user training on how to correctly use and maintain the technology is vital, (iv) the fabric may not be easily accessible in some rural areas.

Wood filtration system combined with GAC (WFSGAC)

WFSGAC (Figure 4) is a novel low-cost gravity-driven drinking water technology developed and optimized by Siwila & Brink (2018d). The system uses 2.54 cm long wood filter elements of 2.54 cm diameter from indigenous tree species coupled with GAC for PoU water treatment under a 2.6 m gravity head. During operation, peeled wood filters are firmly clamped in a 10 cm flexible pipe which is then connected to the end of the 200 cm flexible pipe via connectors (Figure 4). The system uses about 80 g GAC normally reused during wood filter replacement. It is fed with raw water from a Perspex column, 60 cm long and of 10.5 cm diameter. The combined system consistently produces very clear drinking water of turbidity <5 NTU with pleasant color, odor, and taste. When tested using *Combretum erythrophyllum* (umhlalavane) and *Salix mucronata* (Umzekana) tree species, it recorded 100% removal for

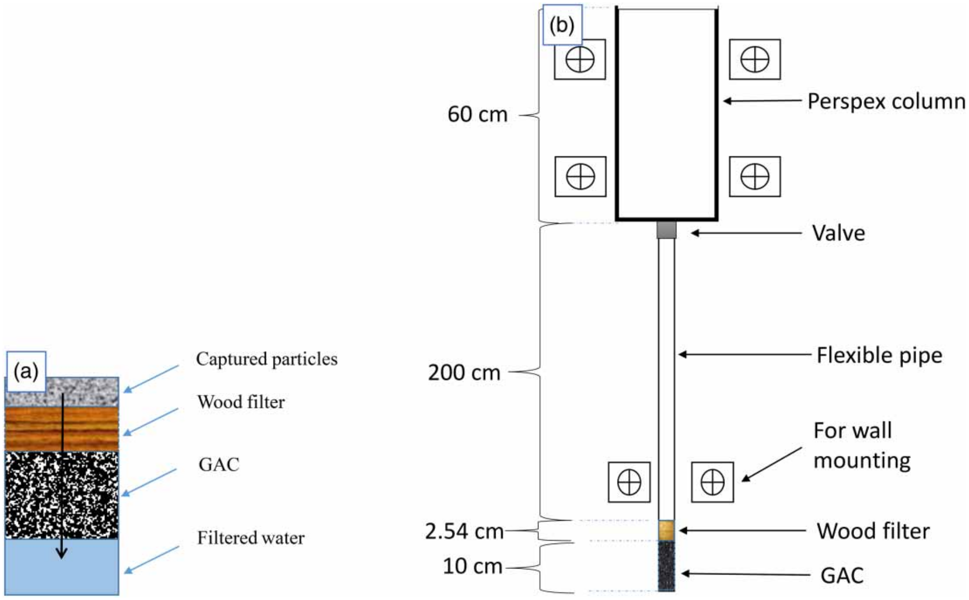

Figure 4 | Combined wood and GAC filtration: (a) process schematic diagram and (b) designed filter system.

indicator bacteria. The combined system can also significantly remove heavy metals: Fe, Pb, nickel (Ni), aluminium (Al) and zinc (Zn) above 90%, and copper (Cu), As, chromium (Cr), Cd and Mn above 50%.

Advantages

(i) Made from small easily replaceable wood pieces, (ii) locally available, (iii) easy to fabricate, (iv) wood is a renewable material, (iii) significant bacterial and particle removals, (iv) significant improvement in treated water's acceptability aspects, (iv) added benefit of heavy metal removal.

Limitations

(i) Relatively laborious to operate and maintain, (ii) low flow rates, (iii) user training on how to correctly cut, preserve and fix the wood pieces is necessary, (iv) potential of introducing harmful substances into the water especially if the GAC malfunctions.

Drip filter system

Distributed under the name DrinC, the DFS (Figure 5(a)) is a low-cost, ceramic candle filter system. The filter is normally wedged between two 20 L buckets and has a 0.2 μm, silver-impregnated ceramic shell-containing activated carbon (DrinC 2017). The treated water gets disinfected through contact with silver. The ceramic candle is sometimes covered with a filter sock to trap some particles and larger debris (e.g. leaves and insects) from the raw water. Particles and debris are removed, followed by microbes down to 0.2 μm as water flows through the system. Raw water from the top bucket drips through the ceramic candle into the bottom bucket, fitted with a tap for drawing drinking water. According to DrinC (2017), the candle filter must be replaced after 1 year's use. It is advisable to shake it every 3 months to dislodge debris and prolong its life and ensure that the carbon stays loose. Furthermore, the activated carbon lasts for about 6–8 months. The system flow rate can be up to 318.24 L/day when the system is new, but it falls over time (Siwila & Brink 2018a). The DFS costs around 600 South African Rand (ZAR) (44 US$) within South Africa.

Advantages (DrinC 2017; Siwila & Brink 2018a)

(i) High user acceptability due to ease of use, simple installation and significant visual improvement in treated water, (ii) high bacterial and particle removal, (iii) long life span if filter remains unbroken, (iv) can yield clean water for a long time if properly maintained.

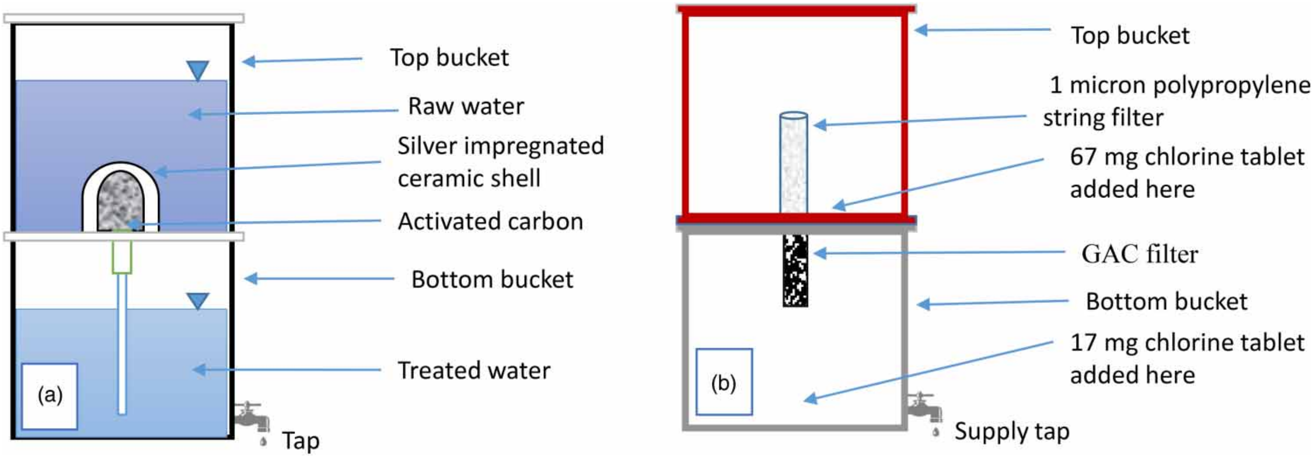

Figure 5 | PoU system schematic drawing: (a) DFS and (b) GWS.

Limitations (DrinC 2017; Siwila & Brink 2018a)

(i) User education is needed to keep the filter and receptacle clean, (ii) ongoing technical support needed, (iii) may not be useable with very turbid waters due to potential clogging problems, (iv) lack of residual protection can lead to recontamination, (v) continuing user education needed.

The gift of water filter system

The GWS (Figure 5(b)) is a low-cost PoU technology primarily developed to combat waterborne diseases and health-related problems in Haiti (Gift of Water Inc. 2017). The two-bucket system employs a 1 micron (μm) string filter, a GAC filter and Aquatabs. Aquatabs are chlorine tablets made of sodium dichloroisocyanurate (NaDCC) which dissolves in water to release hypochlorous acid (HClO) that disinfects the water (WHO 2003; CAWST 2011). A 20 L top bucket, with a 67 mg Aquatab tablet, is filled with raw water and left for 30 minutes. Then a 17 mg Aquatab tablet is added to the bottom 20 L bucket for post-chlorination, to prevent recolonization by most bacteria (Siwila & Brink 2018b). Placing the top bucket on the bottom bucket activates a check-valve. This enables water to flow into the bottom bucket, moving in transit via the string and GAC filters. The string filter removes particles and larger microbes like protozoa, while the GAC filter removes organic compounds and excess chlorine (Gift of Water Inc. 2017). Users obtain treated water through a tap fixed near the base of the bottom bucket. Gift of Water Inc. (2017) recommends replacing the carbon filter every 6 months. The GWS system costs US$25 in the USA, and its estimated flow rate is 1123.2 L/day (Gift of Water Inc. 2017).

Advantages (Gift of Water Inc. 2017; Siwila & Brink 2018a)

(i) Includes a string filter able to pre-treat turbid water, (ii) high bacterial elimination, (iii) chlorine concentration remains high enough to prevent recontamination, (iv) can yield safe water for a long time, (v) user acceptability due to ease of use, fast filtration rate and acceptable taste.

Limitations (Gift of Water Inc. 2017; Siwila & Brink 2018a)

(i) High initial costs due to shipping requirements, (ii) continuing user education needed, (iii) ongoing technical support needed, (iv) ongoing maintenance costs, (v) concerns about potential long-term carcinogenic effects of disinfection-by-products, (vi) need for regular filter replacement.

Comparison and evaluation of the PoU technologies

This section gives a comparative analysis of each system based on the comparison framework. Although the comparative analysis of the drinking water technologies shows that none can totally remove all pollutants (Table 4), they can all improve drinking water security in many parts of the world. It is necessary to appreciate that most PoU technologies are normally not meant for removal of chemicals (Siwila & Brink 2018a). This may not be ideal everywhere but there is enough room for improvement particularly on the three novel technologies.

Removal of indicator bacteria

All of the five evaluated PoU technologies can remove over 96% of *E. coli* and fecal coliforms from water (Table 4). Only GWS, DFS and WFSGAC can completely eliminate indicator bacteria. With proper technology use and maintenance, these may affordably supply safe water in various settings. Long-term sustainable bacterial removals are technically more assured for GWS due to the use of chlorine tablets in both the top and bottom buckets. The drawback with GWS is the potential for the production of disinfection-by-products and objectionable taste especially if the GAC, which removes excess chlorine, fails during use (Siwila & Brink 2018a). Bacterial diseases (cholera, acute bacterial gastroenteritis, dysentery, meningitis, typhoid, etc.) cause the most deaths. According to WHO (2016), about 502,000 diarrhea deaths occur each year in much of the developing world due to consumption of contaminated water. This is roughly 58% of the total deaths caused by poor water, sanitation and hygiene as a whole (WHO 2016). Therefore, the first and most important step in the battle against consumption of contaminated water is removal of all bacteria (McAllister 2005) and improvement of acceptability aspects of water, so that users do not opt for water that is more appealing but is actually unsafe (CAWST 2017; WHO 2017a; Siwila & Brink 2018a). Removal of other contaminants (viruses, chemicals, heavy metals, etc.) can be considered based on resource availability and technology advancement (McAllister 2005) as well as some regional needs or situational analysis.

Improvement of acceptability aspects of water

Another important consideration in evaluating the performance of PoU drinking water systems is the ability to improve the acceptability aspects of water (suspended solids, turbidity, color, odor and taste). Poor acceptability of water can lead to indirect health impacts if consumers lose confidence in the treated water and drink less water or opt for options that may not be safe (McAllister 2005; Sullivan *et al.* 2005; WHO 2017a). All the five evaluated PoU technologies can substantially improve the acceptability aspects of water (Table 5). The best performance in this regard was depicted by ISSFGeoGAC, WFSGAC and DFS (Table 5). For ISSFGeoGAC, this is most probably due to combined removal mechanisms as highlighted earlier. Whereas for WFSGAC, the excellent improvement in the acceptability aspects could be due to the low flow rates (Table 4) provided by the wood filter elements and subsequent large empty bed contact time >20 min (Siwila & Brink 2018d). Likewise, DFS exhibits relatively low flow rates (Table 4) allowing more contact time between water and the GAC.

Heavy metal removal

Table 4 shows that ISSFGoeGAC, WFSGAC and DFS can appreciably remove heavy metals. Although heavy metal removal may still be enhanced, it is an added benefit and may make the PoUs more feasible in many places. It is perceived that due to the presence of GAC, the GWS is likewise able to remove heavy metals. BidimSEQFIL may not remove metals due to its material combination. Generally, heavy metal removal without the inclusion of advanced processes or adsorption materials, e.g. GAC, is difficult for most low-cost methods.

Flow rates

With the exception of the WFSGAC, all the evaluated technologies can treat water >240 L/day (Table 4). This is satisfactory for PoU purposes in homes or small settings such as health centers, schools, etc. (WHO 2016). Although flow rates for WFSGAC may not deliver enough drinking water for a small setting, it can meet drinking water needs for a couple of people, the more so if two or three systems are run in parallel (Siwila & Brink 2018d). According to The Sphere Project (2011), basic water needs are about 7.5–15 liters/capita/day. Therefore, all the evaluated systems with the exception of WFSGAC can meet basic water needs. However, if a few units are operated in parallel WFSGAC may also meet basic water needs (Siwila & Brink 2018d).

Quantitative and qualitative comparison

The comparison framework decision matrix (Table 6), qualitative comparison (Table 5) and quantitative comparison (Table 4) clearly show that all the PoU technologies are viable for adoption depending on a combination of most desired and least desired factors. Good judgement by the engineers or implementers is henceforth critical for a PoU technology to be adopted or further improved. The specialized comparison framework is useful to low-cost PoU water treatment implementers to determine the level to which a PoU technology is suitable in relation to other viable options. The weighted scores indicated that the five evaluated technologies can be ranked from most promising to least promising as follows: (1) ISSFGeoGAC, (2) DFS, (3) GWS, (4) BidimSEQFIL, and (5) WFSGAC. Therefore, DFS ranked higher than GWS between the commercial PoU systems; this is especially true in relation to sub-Saharan Africa due to the shipping cost associated with GWS. ISSFGeoGAC is the best option amongst the three novel technologies though it still requires further optimization in terms of ease of use, ease of deployment and cost (all these factors are mainly dependent on system configuration and material combination). WFSGAC is least favorable due to the observed very low flow rates while BidimSEQFIL is relatively laborious.

Evaluated novel PoU technologies: potential for adoption

The novel technologies were comparatively ranked from best to least promising as shown in Figure 6. The advantages and limitations of each evaluated low-cost and non-advanced PoU technologies have been highlighted. ISSFGeoGAC was found to be the most promising amongst the three novel technologies. Further optimization of such a combined system might result in an efficient and user-friendly PoU technology useful to many communities and situations. The weighted scores were principally based on Table 2 definitions, comparisons in Tables 4 and 5, process and material combinations of each evaluated system, and reports by various researchers (most of which are referenced in Table 1) as well as the author's experience during the technology installations and application tests.

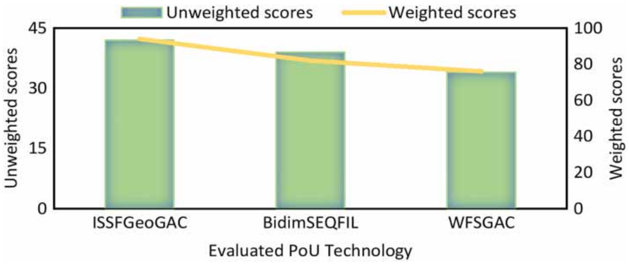

Figure 6 | The evaluated novel technologies comparatively ranked from best to least promising (left to right).

CONCLUSIONS AND RECOMMENDATIONS

ISSFGeoGAC has been identified as the most viable for adoption amongst the three novel technologies. This is because of its simple and robust design coupled with contaminant removal effectiveness, raw material availability and acceptability of its treated water. The novel technology can be adopted as is, but further improvement is suggested. The proposed improvements include addition of a treated water storage compartment and an inbuilt disinfection step to prevent recontamination. Improper storage of treated water has been reported to cause recontamination (Jagals *et al.* 2003; Potgieter *et al.* 2009; Curry *et al.* 2015). The two commercially available PoU systems evaluated have shown similar performance and acceptability potential. These may help improve water security in much of the third world, especially if manufactured locally and materials (spare parts, chemicals, etc.) are guaranteed near or around the places of use. In general, the novel low-cost water treatment systems can reduce (≥87%) particles and eliminate (≥96%) *E. coli* and fecal coliforms from drinking water by physical, biological, adsorption, and chemical processes or a combination thereof. Performance largely depends on filter media, pore sizes and additional treatment processes.

Although it is difficult to choose which type of PoU technology is best for all applications due to many factors required for different situations and resource availability, this study has demonstrated that it is possible to qualitatively and quantitatively compare low-cost PoU technologies. If resources allow, each technology being comparatively evaluated should be tested under similar conditions, e.g. using same test water characteristics and all three test organisms recommended by the WHO evaluation scheme and those proposed in this study. A combination of laboratory and field testing to ascertain removal performance sustainability and other criteria, e.g. flow rates, social acceptability and maintenance requirements, is recommended. Although research outcomes for improving safe water needs in poor communities are primarily met by the development of novel low-cost drinking water systems, field testing helps to establish suitability and sustainability of novel technologies in satisfying the needs of intended users. Adequate training is also proposed wherever the evaluated technologies are to be used so that users can correctly use and maintain the devices.

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