REVIEW ARTICLE

Ceramic water filter for point-of-use water treatment in developing countries: Principles, challenges and opportunities

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H I G H L I G H T S

- CWF is a sustainable POU water treatment method for developing areas.
- CWF manufacturing process is critical for its filtration performance.
- Simultaneous increase of flow rate and pathogen removal is a challenge.
- Control of pore size distribution holds promises to improve CWF efficiency.
- Novel coatings of CWFs are a promising method to improve contaminant removal.

G R A P H I C A B S T R A C T

Ceramic Water Filter

A R T I C L E I N F O

A B S T R A C T

Drinking water source contamination poses a great threat to human health in developing countries. Point-of-use (POU) water treatment techniques, which improve drinking water quality at the household level, offer an affordable and convenient way to obtain safe drinking water and thus can reduce the outbreaks of waterborne diseases. Ceramic water filters (CWFs), fabricated from locally sourced materials and manufactured by local labor, are one of the most socially acceptable POU water treatment technologies because of their effectiveness, low-cost and ease of use. This review concisely summarizes the critical factors that influence the performance of CWFs, including (1) CWF manufacturing process (raw material selection, firing process, silver impregnation), and (2) source water quality. Then, an in-depth discussion is presented with emphasis on key research efforts to address two major challenges of conventional CWFs, including (1) simultaneous increase of filter flow rate and bacterial removal efficiency, and (2) removal of various concerning pollutants, such as viruses and metal(loid)s. To promote the application of CWFs, future research directions can focus on: (1) investigation of pore size distribution and pore structure to achieve higher flow rates and effective pathogen removal by elucidating pathogen transport in porous ceramic and adjusting manufacture parameters; and (2) exploration of new surface modification approaches with enhanced interaction between a variety of contaminants and ceramic surfaces.

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1 Introduction

World Health Organization (WHO) reported that 71% of the world's population used improved drinking water

sources that were free from microbiological and priority chemical contamination in 2017 (World Health Organization, 2017,2019a). However, there are vast inequalities among different countries and areas. For example, although 85% of world urban population could access quality drinking water that is free from contamination, the percentage is down to 53% in rural areas. A large effort is still needed in rural areas, especially in developing countries where pathogen contamination of drinking water represents one of the greatest threats to human health (World Health Organization, 2019b). What's worse, in developing areas such as sub-Saharan Africa, Central and Southern Asia and Oceania, centralized water treatment and distribution systems are often unavailable due to political or socioeconomic factors (Peter-Varbanets et al., 2009; World Health Organization, 2019a). In these areas, point-of-use (POU) systems, which improve drinking water quality at the household level, represent a more affordable and effective way to produce water free from contamination.

In practice, a POU technology should be effective, easy to operate, with low maintenance requirement, economically viable, environmentally sustainable and socioculturally acceptable. Chlorination with safe storage, combined coagulant-chlorine disinfection systems, solar disinfection, ceramic water filter (CWF) and biosand filter are examples of current POU technologies (Sobsey et al., 2008; Murphy et al., 2010; Kallman et al., 2011; Geremew et al., 2018). Based on a comprehensive comparison of these technologies (Table 1), CWF is considered among the most practical and sustainable POU technologies with affordable (highly cost effective) and low-maintenance (easy to use, only periodic cleaning needed) features for household water treatment in developing countries (Sobsey et al.,

2008; Clasen et al., 2015). CWFs, produced from a mixture of clay and sieved combustible material, can effectively remove microorganisms and reduce turbidity from water by gravity filtration through porous ceramic media. CWFs can be fabricated into different shapes, such as disk, tube, candle and pot (Fig. 1), which make them suitable for POU application in various situations. Silver impregnation has been conventionally applied to modify CWFs to enhance their performance, particularly for the removal of microorganisms. Silver-modified CWFs are effective at remov-
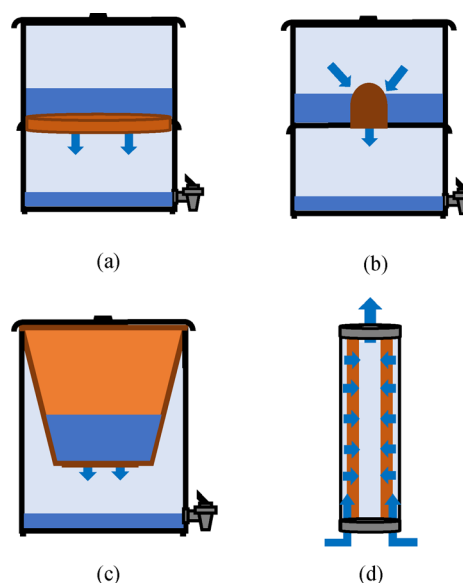

Fig. 1 Schematic of different forms of ceramic water filters: (a) ceramic disk filter, (b) ceramic candle filter, (c) ceramic pot filter, (d) tubular ceramic filter.

Table 1 Comparison of POU treatment technologies used in developing countries[a]

POU technologies	Water quality[b]	Water production[c]	Cost[d]	Ease to use[e]	Overall score	Description
Chlorination	1	3	2	5	11	Hypochlorite liquid or tablets are used to inactivate pathogens in source water.
Coagulation/ Chlorination	2	2	1	2	7	Dry coagulant-flocculant and chlorine as tablets or sachets are added to source water to inactive and settle down pathogens.
Solar disinfection	3	1	5	1	10	Source water is filled in polyethylene terephthalate (PET) or glass under sunlight, allowing UV and heat to inactivate pathogens.
Ceramic water filter	5	2	4	4	15	Porous ceramic media (e.g., pot, disk, candle) with silver coating is used to filter pathogens from source water.
Biosand filter	4	3	3	3	13	Biosand filter is adapted from slow sand filter cover with biofilm, removing pathogens using biological and physical processes.

Note: a) The scoring system was used to compare POU technologies. For each criterion, a technology was ranked from best (with a score of 5) to worst (with a score of 1) and the performance score (5 to 1) represents its relative ranking; b) This score was based on their reduction in Diarrhea reported by Clasen et al. (2015); c) Water production was scored based on producing 20 L within 4 h of applying the treatment described by Sobsey et al. (2008). Due to the different water production methods for these POU technology, the score was only set to 1-3 with 1 for low, 2 for fair, and 3 for good performance; d) This score was based on their cost (dollars/L/year) calculated in Sobsey et al. (2008); e) This score was based on the steps of treatment processes and periodic maintenance.

ing >99% of protozoan (Van Halem, 2006; Abebe et al., 2015) and 90%–99.999% of bacteria (Brown and Sobsey, 2010) and thus have been evaluated for efficacy in reducing rates of diarrheal and other waterborne diseases (Clasen et al., 2004; Morris et al., 2018). Unlike chlorine or thermal disinfection, CWFs do not significantly change the taste or temperature of the water. They are also very effective at reducing the turbidity of the water (Abebe et al., 2016). With proper care as suggested by manufacturers in the user manual, commercial ceramic pot filters, one of the most popular CWFs in the developing countries, have a potential service life of up to 5 years to effectively remove pathogens from raw water without the need for an external energy source or consumable supplies (The Ceramics Manufacturing Working Group, 2011). So far, locally produced CWFs have been successfully applied in more than 20 developing countries (e.g., Cambodia, Guatemala) to improve the drinking water quality (Rayner et al., 2013a). It was estimated that more than 4 million people worldwide used CWFs to prepare daily safe drinking water, which contributed to public health, social and economic benefits (van der Laan et al., 2014).

At the same time, CWFs have some disadvantages that limit their application. First, the relatively low water filtration rates have limited their use. Improved CWF designs that can simultaneously achieve both high flow rate and effective bacterial removal are desirable but remain a great challenge. In addition, CWFs often have limited capability of removing contaminants such as viruses and chemical pollutants (Yang et al., 2019a).

Although the CWF technology has been gaining growing research attentions and witnessing a wide application during the past decades, there have been few critical reviews on the progress of this technology. The objective of this account is to provide 1) a concise summary of the progress of recent CWF research and application with a particular focus on the critical factors and processes that are closely related to CWF performance, and 2) an overview of challenges and opportunities for further improvement for CWF as a POU water treatment technology in developing areas.

2 Critical factors for CWF performance

CWFs are fabricated from a mixture of clay and combustible materials (e.g., rice husks or sawdust) referred as burn-out materials. Filter porous structure is created as a result of the burn-out during the firing process. As shown in Fig. 2, fabrication of conventional ceramic filter includes raw material selection and processing, mixing and pressing, drying and firing, silver application, as well as quality testing. In this section, we focus on the processes whose effects on filter effectiveness have been documented by published reports and peer-reviewed references.

2.1 Raw material selection

2.1.1 Clay source

Clay is the skeleton element of CWF, and its quality and characteristics directly influence filter quality. Earthenware clay is most suitable for ceramic filter production due to its porosity, availability, and low temperature needed for vitrification. In practice, clay physical properties (e.g., shrinkage, plasticity, workability), the persistent availability of clay source, and the leachability of heavy metals/inorganic materials are some key parameters to be considered for clay source selection (The Ceramics Manufacturing Working Group, 2011). Details for clay source test, selection and handling have been described in the instruction manuals of Potters for Peace (PFP) and Resource Development International (RDI) (Hagan et al., 2009; The Ceramics Manufacturing Working Group, 2011). Although clay does not create pore structure directly, Oyanedel-Craver and Smith (2008) found that filters made from different clay sources showed varied porosity, hydraulic conductivity and bacterial removal efficiency. A recent study suggested that high content of sand-rich clay may contribute to the decrease of mean pore size of CWF and thus potentially influence filter flow rate and bacterial removal efficacy (Youmoue et al., 2017). Additionally, the inclusion of diatomaceous earth and MgO components in the CWFs were found to be beneficial for viral removal (Michen et al., 2012; Michen et al., 2013), suggesting that clay composition may also have some influence on filter performance.

2.1.2 Organic combustible material

In the CWF manufacturing process, sieved organic combustible material, also known as burn-out material, is mixed with raw clay for the purpose of creating a paste which is subsequently pressed into various shaped filters. The organic combustible materials are usually burnt out during the firing process to create porous structure that serve as both flow paths for water passage and reaction sites for the removal of various contaminants such as bacteria and virus. The combustible material thus has been identified as a critical parameter on the performance of CWFs. Sawdust and rice husk are the most common combustible materials used in manufacturing CWFs and a global-wide survey reported that 17 in 18 CWF production factories used sawdust or rice husk as the combustible material (Rayner et al., 2013a). In addition, coffee husks, peanut husks and other organic materials that can be pulverized to a suitable size can also be used as combustible materials, depending on their cost and local availability. According to previous laboratory and field studies, the size and amount of combustible material have a strong influence on the filter performance (Kallman et al.,
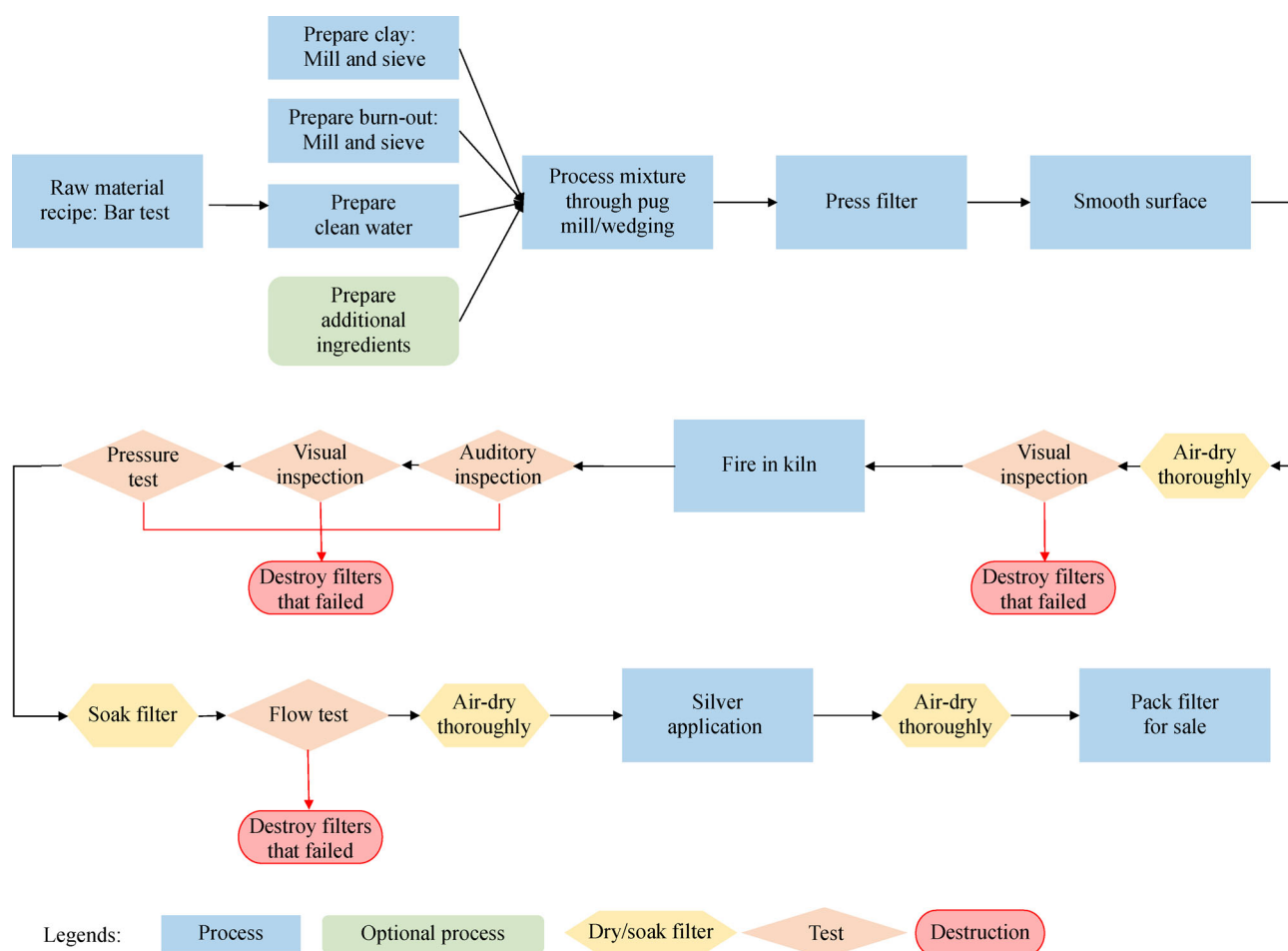
Fig. 2 Ceramic water filter production flow chart. It was re-drawn based on the Ceramics Manufacturing Working Group (2011).

2011; van der Laan et al., 2014; Soppe et al., 2015; Rayner et al., 2017; Van Halem et al., 2017). For example, Van Halem et al. (2017) produced pot filters with a higher flow rate (2-6 times as regular pot filters) by increasing the rice husk content from 24% to 31% (wt.% of dry clay mixture). Combustible material with a larger particle size has also been reported to introduce larger pore sizes of the resulting CWF, which could facilitate a higher flow rate but often resulted in lower microbial removal efficacy (Soppe et al., 2015; Rayner et al., 2017).

2.2   Firing process

The firing process of CWFs generally consists of seven stages that include water smoking (20°C–120°C), decomposition (120°C–350°C), burn-out combusts (350°C–450 °C), ceramic change (350°C–700°C), carbon burns out (700°C–900°C) and vitrification ($<$1000°C) (The Ceramics Manufacturing Working Group, 2011). A detailed recommendation of kiln construction and firing variables has been provided by The Ceramics Manufacturing Working Group (2011). Soppe et al. (2015) observed increased flow rate and slightly decreased microbe removal

efficiency when the maximum firing temperature increased from 800°C to 950 °C, which may be attributed to the small increase of filter pore size with increasing maximum firing temperature. Additionally, the incomplete combustion of the organic materials could lead to the production of substances such as black carbon cores inside the filter during the firing of commercial CWFs (The Ceramics Manufacturing Working Group, 2011; Goodwin et al., 2017). Currently, black CWF was reported to be fired in a reductive atmosphere to improve its virus removal performance (Guerrero-Latorre et al., 2019). The potential impact of the firing atmosphere on the performance of the resulting CWFs, especially for the removal of contaminants other than pathogens, may warrant further investigation in the future.

2.3   Silver impregnation

Silver is typically applied as an antimicrobial agent to modify commercial CWFs after the firing process to enhance the bacterial removal efficiency, and to prevent biofilm growth and recontamination after treatment. The

primary mechanisms for bacterial removal using silver-impregnated CWFs include both physical filtration (e.g., size exclusion and straining) and chemical inactivation (silver disinfection), and silver antibiotic activity occurs during both the filtration process and the subsequent water storage in the receptacle (van der Laan et al., 2014). Previous studies reported that silver-impregnated CWFs could exhibit up to 5 log reduction value (LRV) of bacterial removal (i.e., 99.999%), while CWFs before silver impregnation could only reach an average of 2 LRV (i.e., 99%) of bacterial removal (Oyanedel-Craver and Smith, 2008; Rayner et al., 2013b). The amount of silver applied has been found to strongly influence the bacterial removal efficiency, and thus the silver dose needs to be delicately controlled so that it is sufficient to ensure effective disinfection for a long time (Ren and Smith, 2013). Therefore, understanding of factors governing the silver retention and release behavior from CWFs surface is crucial to evaluate the performance and lifespan of silver-impregnated CWFs.

Several factors have been reported to influence the silver release behavior, including silver impregnation method, silver type, and source water chemistry (Rayner et al., 2013b; Ren and Smith, 2013; van der Laan et al., 2014; Mittelman et al., 2015; Sullivan et al., 2017; Lyon-Marion et al., 2018). Ren and Smith (2013) compared three methods to modify CWFs with silver nanoparticles (nAg) and found that the fire-in method where nAg was applied before firing significantly improved silver retention and decreased its release from CWFs, compared to the paint-on and dipping methods, both of which were introducing nAg after the ceramic firing process. A few previous studies reported that silver release from filters coated with silver nitrate (Ag^+) was greater than those coated with nAg, and the effluent silver concentration was dependent on the amount of silver applied (Rayner et al., 2013b; Sullivan et al., 2017). Additionally, source water chemistry, including ionic strength, pH, ion valence, the presence of natural organic matter and free chlorine, has been found to influence silver release (Rayner et al., 2013b; Mittelman et al., 2015; Sullivan et al., 2017; Lyon-Marion et al., 2018). Laboratory studies reported that the concentrations of leached silver in treated solutions were below the drinking water standard (0.1 mg/L) (Rayner et al., 2013b; Mittelman et al., 2015). In practice, new silver-impregnated CWFs are suggested by manufacturers to rinse with 2–3 pot full of water before use, which could lower the silver concentration in the effluent to levels below 0.1 mg/L (The Ceramics Manufacturing Working Group, 2011). Although silver impregnation shows improved bacterial removal efficiency, there are concerns about the cost associated with the silver application, and the relatively short service life of conventional filters (3–5 years) because the filters would become less effective when the impregnated silver is depleted (Lantagne, 2001; Bielefeldt et al., 2009).

2.4 Source water quality

As CWFs are being used on a global scale for the production of safe drinking water for both household and/or small community, the source water quality can be substantially varied between different applications. While variations in the performance of CWFs have been reported from different areas or/and filter factories, these variations were primarily attributed to the differences in local materials and filter fabrication process, and the role of source water quality remains largely unknown. Among various water quality factors, only limited studies have focused on turbidity and reported its negative impact on CWF performance (water production and/or flow rate) due to pore blocking (Salvinelli and Elmore, 2015; Salvinelli et al., 2016). For silver impregnated CWFs, both physical filtration and silver disinfection are considered important pathogen removal mechanisms. Although water chemistry parameters (e.g., pH, ionic strength, presence of various ions) may theoretically have relatively limited influence on pathogen removal via physical filtration, they can significantly affect the silver release behaviors, and thus affect the filter performance and service lifespan. Detailed and long-term laboratory and field studies are needed to further explore the performance of CWFs in various water sources.

3 Challenges and opportunities

3.1 Flow rate versus microbial removal efficiency

Flow rate and microbial removal efficiency are two performance indicators for CWFs. Filters that can maintain both high flow rates and effective microbial removal would be particularly desirable for end users. As discussed in the previous section, numerous attempts have been taken to improve CWF fabrication (e.g., combustible material processing) for the development of effective and fast-flow CWFs. Table 2 summarizes the flow rate and microbial removal efficiency of CWFs reported in previous laboratory- and field-scale investigations. To allow for the comparison of CWFs made in different shapes, the reported flow rates were converted to the "equivalent" flow rates of a full-size ceramic pot filter with a frustum shape, based on the hydraulic method used in our previous study (Yang et al., 2020). So far, the ceramic pot filter design (Fig. 1(c)), one of the most popular CWFs applied in developing countries, can achieve a balance of 1–3 L/h flow rate and ~2 LRV bacterial removal without silver impregnation (~4 LRV after silver impregnation). For a typical household size with 5 persons, at least 10 L of safe drinking water would be needed on a daily basis (Ren et al., 2013). However, as sediment and particles clog the filter pores, the flow rate decreases. Scrubbing the filter surface provides a temporary benefit but does not prevent

Table 2 Flow rate and bacterial removal efficiency of reported CWFs

Reference/ source	Laboratory/Field work	Flow rate[a] (L/h)	Microbial removal (LRV[b])	Porosity	Average pore size (μm)[c]
Yang et al. (2020)	Laboratory	5.1–6.4	4.5	0.22	1.22
		12.5–15.4	2.1	0.24	1.24
Oyanedel-Craver and Smith (2008)	Laboratory	~2.6	3.0 (w/o Ag coating) 4.0 (w/o Ag coating)	0.37	14.3
		~1.7	2.9 (w/o Ag coating) 3.2 (w/o Ag coating)	0.42	2.0
		~0.61	3.4 (w/o Ag coating) 3.8 (w/o Ag coating)	0.39	8.2
Bielefeldt et al. (2009)	Laboratory/Field	0.8–1.9	2.2–3.8 (w/o Ag coating) 3.2–4.2 (w/o Ag coating)		Not reported
van der Laan et al. (2014)	Field	5.5–21.0	~1 (w/o Ag coating)		Not reported
		2.55	2.5 (w/o Ag coating)		
Van Halem et al. (2017)	Field	5–20	~1.0 (w/o Ag coating)		Not reported
Soppe et al. (2015)	Laboratory/Filed	7–23	2.1–2.9 (w/o Ag coating)		Not reported
PFP[d]	Field	1–3	~2 (w/o Ag coating)	Various from factory to factory	
RDIC[e]	Field	1.8–2.5	~2 (w/o Ag coating)	Various from factory to factory	

Note: a) Flow rate was adjusted for disk bottom diameter and water head to the full size of pot (Fig. 1(c)). Detail for adjustment can be found in Yang et al. (2020); b) LRV, log reduction value;c) Average pore diameter was obtained by the pore size distribution data measured by mercury intrusion porosimetry (MIP); d) Pottery for peace, a US-based non-profit working on ceramic water filter; e) Resource Development International-Cambodia, a non-profit working on ceramic water filter.

long-term clogging. The development of filters that can achieve a higher flow rate while maintaining effective microbial removal remains a challenge. Instigations into manufacturing parameters that can be modified to achieve both high flow rate and effective microbial removal are needed.

Pore size of CWFs is considered a critical parameter that can affect both flow rate and microbial removal efficiency (Soppe et al., 2015; Youmoue et al., 2017). CWFs were prepared using three combustible materials that include irregularly shaped rice husk, spherical/oval shaped starch and tubular shaped recycled paper fiber in our recent study (Yang et al., 2020). Because of the different shapes of combustible materials, the fabricated CWFs had varied pore size distribution patterns, resulting in substantially different flow rates and bacterial removal efficiencies. Particularly, filters prepared using recycled paper fiber showed improved performance with regards to both flow rate and bacterial removal. The best-performed filters (no silver coating) exhibited (1) a fast equivalent flow rate of 13.9 L/h while maintaining a >2 log bacterial removal efficiency (>99%), or (2) >4 log bacterial removal efficiency (>99.99%) with an equivalent flow rate of 5.9 L/h, by simply tuning the amount of the recycled paper fibers to 20% and 15% (i.e., with fiber-to-clay ratios of 20%:80% and 15%:85%), respectively. The improved performance of filters prepared using recycled paper fibers could be attributed to the unique pore size distribution pattern that consists a good balance of both small and medium to large pores. Based on the classic Hagen-Poiseuille law, medium to large pores are required to reach

a high flow rate; meanwhile, the presence of a sufficient number of small pores is essential for achieving a satisfactory bacterial removal efficiency. Results suggested that fibrous materials like recycled paper fiber may potentially be used as effective combustible materials for CWF fabrication to create balanced and interconnected pore structure. Meanwhile, Soppe et al. (2015) observed that average flow rate of CWFs could be increased by using larger quantities of rice husks but without reducing the bacterial removal effectiveness. Further information and analysis of the pore size distribution of these filters are needed to explore the critical factors for improved CWFs.

An improved understanding of key factors that affect and control the pore size distribution can provide important insights into guiding the design of CWFs with both high flow rate and bacterial removal. In an initial attempt, a semiquantitative model was developed to explain the role of pore size distribution on the design of optimal CWFs that can balance effective microbial removal and adequate flow rate (Yang et al., 2020). With further information of pore network within porous ceramic using advanced characterization and 3-dimensional imaging techniques, development of more sophisticated pore-scale mathematical and numeric models in the future can be beneficial to direct the design of ceramic filters with controlled pore size distribution and improved performance. In addition, manufacturing parameters other than combustible material can affect the pore size distribution of CWFs. For instance, Oyanedel-Craver and Smith observed different pore size distributions for CWFs fabricated using three different sourced clay materials, and filters prepared from redart clay

had most abundance of small pores and thus highest bacterial removal efficiency (Oyanedel-Craver and Smith, 2008). A comprehensive investigation should be performed in the future to determine the impact of individual manufacturing parameters as well as their combined effect on the pore size distribution of ceramic filters. It also should be mentioned that the flow rate of CWFs may decrease after extended use in the field because of sediment and/or particle clogging. Thus, the long-term performance of ceramic filters prepared using improved recipes should be evaluated under settings relevant to practical applications.

3.2   Removal of various classes of contaminants

Conventional CWFs are designed to primarily target the removal of microbial pollutants with relatively large sizes (e.g., bacteria, protozoa). Pore sizes of conventional CWFs are typically in the range of 0.1-100 μm (Oyanedel-Craver and Smith, 2008; Brown and Sobsey, 2010), and thus they are not able to retain small-sized pathogens (e.g., virus) and commonly-found chemical pollutants (e.g., arsenic, fluoride, chromate) through physical filtration. Additionally, because of the negatively charged ceramic surface, CWFs with and without silver coating generally exhibit low affinity with virus and negatively- and non-charged chemical pollutants, resulting in negligible capture of these pollutants through adsorption as well. For example, previous studies reported that CWFs only had viral removal efficiencies in the range of 0.21 to 1.6 LRV in long-term testing (Brown and Sobsey, 2010; Salsali et al., 2011; van der Laan et al., 2014), with no significant differences between silver-impregnated and non-impregnated CWFs (van der Laan et al., 2014). The low removal efficiency for virus and various chemical pollutants represents a major challenge for conventional CWFs.

Chemical pollutants are generally removed through the interaction (e.g., adsorption, surface precipitation) with surface of (modified) CWFs. To improve the removal of chemical pollutants, a practical approach is to modify the ceramic surface with desired coatings to enhance the affinity with the target pollutants. For instance, ceramic disk filter modified with ferric iron was developed to improve arsenic removal, and the filter performance was strongly affected by the ferric iron loading (Robbins et al., 2014). Recently, lanthanum (La), an abundant rare earth element with relatively low cost, was applied in our study as a novel and effective coating for ceramic materials to target the removal of negatively-charged arsenate (As(V)) and non-charged arsenite (As(III)) (Yang et al., 2019a). The La-coated ceramic material showed substantially enhanced capture of both As(V) and As(III) with the sorption capacities of 24.8 and 10.9 mg/g, respectively. On the contrary, negligible adsorption of As(V) or As(III) was observed for bare ceramic material without La coating. Furthermore, a prototype La-coated ceramic disk filter

could efficiently treat ~14500 and 3200 pore volumes of solutions highly contaminated with As(V) and As(III) (~125 μg/L) below the drinking water standard (10 μg/L), respectively. The improved removal of As(V) and As(III) can be attributed to the formation of $LaAsO_4$ surface precipitates and La involved inner-sphere surface complexes, respectively. Notably, the interaction between chemical pollutants and La coating strongly depends on the chemical composition and properties of the La coating, which can be controlled by the coating process. Thus, a delicate control of the La coating temperature is critical to obtaining optimal La components that favor the removal of various chemical pollutants (Yang et al., 2019b).

Since most viruses hold negative charges in natural aquatic environments (pH 5–8), modification of ceramic surface with positively charged chemical coatings has been applied to promote virus removal via enhanced electrostatic interaction (Table 3). Michen et al. (2013) reported that ceramic filters amended with MgO increased the removal of bacteriophages MS2 and PhiX174 by up to 4 LRV, while the filter performance decreased sharply after 2000 pore volumes of treatment. Wegmann et al (2018 a, b). found that modification of ceramic microfilters with Zr $(OH)_x$ and Y_2O_3 greatly increased the isoelectric point (pH_{IEP}) of the filters from < 3.1 to 5.5–9 and 8–10, respectively. Thus, the $Zr(OH)_x$- and Y_2O_3-modified ceramic filters showed remarkably increased removal efficiency of MS2 (up to 7 LRV). Meanwhile, the authors observed that the presence of humic acid negatively impact the filter performance, and the virus removal efficiency also significantly decreased after extended operation (Wegmann et al., 2008b). In addition to virus removal, it is worth mentioning that some novel coatings such as nano TiO_2 and nano ZnO have also been applied as alternative antimicrobial agents to silver for ceramic modification to improve the cost-effectiveness of bacterial removal in the laboratory-scaled studies (Lucier et al., 2017; He et al., 2018; Huang et al., 2018).

As more and more low-cost, environmentally benign and novel coatings are being explored for ceramic surface modification, it holds promises to develop modified CWFs with improved performance for the removal of various small-sized chemical and microbial pollutants. Since the properties of surface coatings and thus their interaction with pollutants are strongly influenced by water chemistry parameters, further investigations are required to determine the long-term filter performance in both laboratory and field scales under various source waters. The safety and leaching behavior of the novel coatings should also be carefully evaluated before field application.

4   Conclusions

CWFs, produced from local-sourced clay and combustible material is an affordable, effective, low-maintenance and

Table 3 Studies exploring CWFs surface modification besides silver impregnation

Modification component	Modification method	Target contaminants	Removal efficacy/capacity[a]	References
Nano TiO_2	Painted-on[b]	Escherichia coli	>90%	He et al. (2018)
ZnO	Painted-on	Escherichia coli	2.19–2.97 LRV	Huang et al. (2018)
TPA[c]	Painted-on	Escherichia coli	6.24 LRV (raw filter 4.34 LRV)	Zhang and Oyanedel-Craver (2013)
Iron oxide	Submersed in Fe^{3+} solution → baked at 110°C (4h) → 550°C (3h)	Arsenite/ As(III)	Treating 49–1619 bed volumes of arsenic-contaminated solution under 10 μg/L	Robbins et al. (2014)
		Arsenate/ As(V)		
Lanthanum components	Submersed in La^{3+} solutio → thermally treated for 3h	Arsenite/ As(III)	Treating ~3200 pore volumes of As(III)-contaminated solution under 10 μg/L	Yang et al. (2019a,b)
		Arsenate/ As(V)	Treating ~14500 pore volumes of As(V)-contaminated solution under 10 μg/L	
		Chromate/ Cr(VI)	13 mg/g	
		Virus (MS2)	>5 LRV	
Y_2O_3	Submersed in Y_2O_3 colloids → dried at 80°C (12h) → calcined at 500°C–1040°C (1h)	virus (MS2)	Up to 6.5 LRV	Wegmann et al. (2008a)
$Zr(OH)_x$	Submersed in $Zr(OH)_x$ colloids → dried at 150°C (12h) → calcined at 250/300/400°C (1h)	virus (MS2)	6.2–6.6 LRV (pH5) 4.0–6.9 LRV (pH7) 3.7–7.4 LRV (pH9)	Wegmann et al. (2008b)
MgO	Fired-in[d]	virus (MS2, PhiX174)	0.3–4.7 LRV (MS2) 0–4 LRV (PhiX174)	Michen et al. (2013)

Note: a) Removal efficacy/capacity: removal capacity was used to indicate CWFs performance for chemical pollutant removal; b) Painted-on: using a paint brush to paint the coating chemical solution to filter surface, then air-dried; c) TPA: poly (trihydroxysilyl) propyldimethyloctadecyl ammonium chloride; d) Fired-in: coating chemical was added to clay mixture before firing.

sustainable technology appropriate for POU household water treatment in developing areas. This account focuses on the critical factors for CWFs performance, including manufacturing processes and source water quality. Two technical challenges that limit the further application of CWFs are discussed in detail, including simultaneous improvement of filter flow rate and bacterial removal, and efficient removal of various chemical and microbial pollutants. Great efforts from researchers and CWFs manufacturers have been taken to (1) improve CWFs with both high flow rate and effective bacterial removal by optimizing pore properties during the filter manufacturing processes, as well as (2) enhance CWFs removal efficacy of various waterborne contaminants by novel chemical modification on ceramic surface. According to the brief summary of progress for CWFs research and application in last decades, including our research, several future research directions are proposed to guide the design, manufacture, and application of improved CWFs for POU water treatment in developing countries.

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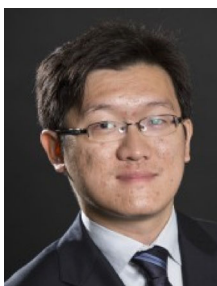
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