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A review of the impact of testing conditions on the performance and quality control of locally manufactured, point-of-use ceramic water filters

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Abstract:

The microbial removal performance of point-of-use ceramic water filters (CWFs) varies widely depending on the manufacturing practices and testing conditions. A critical review of the most recent studies on CWFs, published between 2009 and 2020, was performed. The goals of this review were to (1) identify inconsistencies in testing procedures used to assess CWF microbial removal performance and (2) discuss methods of standardization that could improve our understanding of the effects of manufacturing parameters on CWFs used worldwide. First, the impacts of manufacturing materials on CWF performance were reviewed and analyzed. Our review of manufacturing variables shows that CWFs made with smaller grained clays, sawdust, and silver nanoparticles have slightly higher log removal values (LRVs) compared to CWFs made with larger grained clays, rice husks, or silver nitrate. Next, we reviewed the potential impacts of testing conditions (focusing on influent water chemistry) on CWF performance. The variability in CWF testing conditions makes it difficult to aggregate the data on CWFs to show the impacts of manufacturing conditions on microbial removal. Standardized methodologies for CWF testing are one potential solution for providing more useful information highlighting the effect of manufacturing conditions on CWF performance. We discuss the application of two available CWF testing protocols from the United States Environmental Protection Agency (USEPA) and World Health Organization (WHO) for their applicability as standardized quality control techniques. The application of either of these protocols will bring greater consistency and easier comparisons between studies on CWFs. Our assessment of the impacts of manufacturing and testing conditions on CWF performance provides insights on the benefits of the USEPA and WHO standardized testing schemes. The application of a standardized quality control technique could improve CWFs in the field by identifying how differences in manufacturing affect performance.

Water Impact Statement: Ceramic water filters (CWFs) are a point-of-use drinking water treatment device in under-served communities worldwide. Here, we demonstrate the need for coordination among researchers with regards to testing the CWF microbial removal performance in laboratory and field settings. We also discuss standardized quality testing protocols that could improve data generated for CWFs. This will lead to more accurate comparisons between studies and the production of better-performing CWFs.

1. Introduction:

Ceramic water filters (CWFs), a physical point-of-use (POU) drinking water treatment device, have been studied by many researchers.[1-5] CWFs are effective against a wide range of contaminants including bacteria[6-10], organic and inorganic chemicals[10], protozoa[11], and viruses[12-15]. The reduction in pathogenic microorganisms has led to reductions in diarrheal rates ranging 60-80% in Colombia[7], South Africa[6, 16], Cambodia[12, 17-19], and other locations around the world. Compared to other POU water treatment techniques, CWFs are a socially acceptable technology because they are easy to use, low cost, utilize local craftsmanship, and do not impart a smell or taste to the water (Table S1).[20-23] In terms of limitations, the heterogenous composition of the raw material affects the manufacturing process and the quality of the CWF.[7, 23, 25-27] Microbial removal of CWFs and the strength of the ceramic matrix varies depending on the quality of the materials used in its construction.[7, 23, 25-27] At the user level, regular cleaning is required for appropriately functioning CWFs and the flow rate (which ranges 1-5 L/h) decreases over the lifetime (about 1-2 years) of the device.[1, 9, 21, 23, 24]

About 50 CWF factories worldwide utilize locally sourced materials and varied methodologies to manufacture their filters.[3, 26, 28, 29] This makes the CWFs produced at each factory unique. CWFs can be categorized by their burnout material, shape, and antimicrobial coating. Clay, water, and burnout material are mixed at factory-specific ratios that are dependent on the properties of each material.[1, 3, 4] The clay is obtained from mines near the CWF factory (the composition changes depending on the location), but the burnout material is usually rice husks or sawdust (obtained close to the CWF factory).[1, 3, 27, 30] The CWFs are pressed into shape using a manual or hydraulic press, then air dried and fired.[3] CWFs can take on several shapes including disk, straight walled, curved wall, or bowl shapes.[1, 3, 30] The CWFs that are used in the field are usually coated in either silver nanoparticles (AgNPs) or silver nitrate ($AgNO_3$) which improves the reduction in microbial load.[1, 3, 9, 27, 31].Some studies have seen success with copper[32-34] or zinc coatings[35], but these are not frequently used in field applications.

The body of literature discussing CWF microbial removal performance faces a challenge due to the variety of testing methodologies that are used. The lack of consensus in testing methodologies hinders comparisons between studies and the improvements that CWF manufacturers can obtain from the data in the literature. This review addresses this knowledge gap by summarizing the effects of testing methodology on the microbial removal of a CWF. The goals of this review are to (1) examine the literature to identify inconsistencies in testing procedures used to determine microbial removal performance in CWFs and (2) discuss potential protocols that can be used to improve and standardize performance testing.[1, 2, 4, 36, 37] The review is organized into three sections: (1) effect of manufacturing materials on CWF microbial removal performance, (2) variability in testing that is prevalent in the literature, (3) discussion of standard performance assessments and their potential benefits and limitations for application in the field. In order to accomplish this, we reviewed the most recent literature on CWFs (2009-2020).

2. Methods:

The studies for this literature review were found by searching the following databases: ScienceDirect, Scopus, Web of Science, SpringerLink, Wiley Online Library, Taylor and Francis, American Chemical Society, and Royal Society of Chemistry. The search terms were "ceramic water filter" OR "ceramic pot filter" AND "point-of-use". Only studies written in English and published in peer reviewed journals from 2009 to 2020 and containing the phrases indicated above in the title, abstract, or keywords were considered for this review. This selection was based on the last major literature review of CWF manufacturing practices, which was undertaken in 2009 in *Current practices in manufacturing of ceramic pot filters for water treatment*.[1, 3, 36] Throughout this paper, claims are made about variables of interest based on ranges of log removal values (LRVs) collected from the literature.

Table 1 summarizes the 79 papers were evaluated here. Most of the papers (62%) were laboratory studies. While these papers covered a range of topics, the majority (68%) addressed microbial removal. This study will focus on CWFs coated in silver because this is what is usually applied at CWF factories, however, it should be noted that many novel antimicrobial compounds such as copper and zinc, among others have been also tested. About 83% of CWF manufacturers use AgNPs and a smaller group (17%) uses $AgNO_3$.[1, 3, 32-35, 36]

CWFs have been studied rigorously since their invention in 1981.[3] While a large body of literature has been generated examining CWFs, the testing conditions used to quantify their performance have been inconsistent. Table 1 summarizes studies analyzing the performance of CWFs manufactured under a wide variety of conditions between 2009 and 2020. A diverse set of testing conditions, including the type of microorganism and testing solution, have also been applied for CWF testing (Table 1). Studies are grouped into two categories based on the influent solution used for testing: natural water and synthetic solutions. A subgroup of studies that used *E. coli* to quantify microbial removal performance by silver coated CWFs can be found in Table S2. These studies were separated to more closely analyze the variety of testing conditions that have been utilized to study CWFs and how this could affect LRV. This table further analyzes the subgroup in terms of filter construction (clay source, burnout material, filter shape, and silver coating), methods (influent addition and sampling schedules and influent bacteria addition) and results (bacterial removal).

Table 1: Studies, filters, and microorganisms featured in papers evaluated in this review

Type of Study	Number of papers	Percent
Laboratory	49	62
Field studies	17	21
Modelling	6	7
Review	4	5
Field/laboratory	3	4
Filter Shape[a]		
Straight walled	27	34
Disks	17	21
Candles	9	11
Bowl	4	5
Other	7	9
Not reported	16	20
Clay Material[a]		
Locally sourced	64	78
Industrially manufactured	18	22
Burnout Material[a]		
Sawdust	30	38
Rice husks	12	15
Not reported	29	37
Other (flour, greenfiber, etc.)	7	9
Coating[a]		
Silver nanoparticles	29	34
Uncoated	22	26
Silver nitrate	11	13
Silver, no details	3	4
Copper	3	4
Not reported	17	20
Microorganism of Interest[a,b]		
Bacteria	43	75
E. coli	38	70
Total coliform	9	17
Other[c]	7	13
Viruses	11	20
MS2 Bacteriophages	11	85
Other[c]	2	15
Protozoa	3	5
Cryptosporidium parvum	2	50
Other[c]	2	50
Testing Solution		
Natural water (collected surface, ground, rain, or tap water)	38	70
Synthetic solution (deionized water with additives)	16	30

[a] Some papers evaluated multiple filter shapes, burnout materials, clay types, or coatings. These studies are counted more than once, which is why the total number of studies reported is more than 79.

[b] The percentages presented under the subcategories of the microorganisms of interest (i.e. *E. coli*, MS2 bacteriophages, etc.) are representative of the subcategory. This means that the papers written about *E. coli* make up 70% of the papers about bacteria, not 70% of the total.

[c] The "Other" categories in this section are groups of studies that have examined the removal of less common organisms. The most important types of microorganisms have been extracted and listed as subgroups.

3. Impact of manufacturing variables on ceramic water filters performance

Every CWF factory produces filters using different materials and procedures.[1, 3, 25, 27, 38] Table 2 shows a compilation of studies including manufacturing parameter, any sources of variability in LRV, an example, and a summary of the current understanding of the effect that the parameter has on microbial removal performance. CWFs made with clays of a smaller grain size (such as Red Art clay), sawdust, and silver nanoparticles tend to have a higher LRV than those made with larger grained clays (local clays), rice husks, and silver nitrate (Table 2).[1, 26, 27, 39] The *E. coli* removal for CWFs manufactured with small-grained clays, sawdust, and AgNPs ranges 2.06-4.10 LRV (Table 2). CWFs that are manufactured with locally sourced (large grain) clays, rice husks, and $AgNO_3$ have an LRV range of 0.96-5.7 (Table 2). This range has a higher maximum because $AgNO_3$ leaches rapidly from the surface of the CWF.[15, 27, 40-42] The rapid leaching leads to a higher initial microbial removal that is unsustainable over time.[15, 27, 40] In the long term, CWFs made with small-grained clays, sawdust, and AgNPs have a higher microbial removal.

Table 2: Effect of manufacturing parameters on CWF performance

Parameter	Source of variability	Conditions	LRV (*E. coli*)	Source (LRV)	Current understanding of parameter's effect on microbial removal
Burnout material	Type	Sawdust	2.37±0.239	26	The type, grain size, and percent weight of burnout material changes the pore structure of the CWF. Larger pores decrease the removal of the filter.[11, 26, 43, 44]
		Rice husks	0.96±0.079		
	Grain size	0.250-0.595 mm	2.06±1.330		
		1.19-2.38 mm	1.87±0.261		
	Percent weight	13.7%	4.43±0.402		
		20%	2.83±0.265		
Clay	Minerology	Iron oxide	8.0*	45	Viruses are adsorbed onto and inactivated by clay enhanced with these minerals.[45]
		Aluminum oxide	1.9±0.22*		
		Unmodified	0.55±0.49*		
		Tanzania	4.3±0.6	27	Local clays can influence LRV.[27, 39]
		Nicaragua	3.0±0.7		
	Grain size	6.3 µm	3.5	39	Small clay grains produce small pores and high LRV.[39]
		44.7 µm	1.7		
Silver coating	Type	Silver nitrate ($AgNO_3$)	5.7**	27	$AgNO_3$ releases more Ag^+ than AgNPs, which leads to a higher initial LRV. AgNPs are retained better, leading to a higher long term LRV.[15, 27, 40-42]
		Silver nanoparticles (AgNP)	4.1**		
	AgNP size	46.7 nm	3.7	10	Small, monodisperse AgNPs have a greater available surface area, allowing for more interactions with microorganisms.[10, 40]
		104.5 nm	3.2		
	Polydispersivity of AgNPs	0.12-0.18	3.7		
		0.58	3.2		

*MS2 bacteriophage removal. All other LRV values are reported for *E. coli*.
**LRV in this study was measured over time, this value represents an approximation of the LRV when filter operation reaches steady state (5 days).

As mentioned previously, manufacturers coat their CWFs in either AgNPs or $AgNO_3$.[1, 3] A recent WHO document (2018) reported that silver should not be used as a primary disinfectant.[46] In water purification using a CWF, the primary mechanism of disinfection is mechanical filtration in which microorganisms are physically trapped within the small pores of the filter.[10, 12, 35, 42, 43] Coating the CWF in silver can reduce the viability of the microorganisms trapped within the surface layers of the CWF and biofilm buildup.[10, 15] Silver-coated ceramics are advantageous because they prolong the lifetime of the CWFs. The silver that is leached from AgNP and $AgNO_3$ coated CWFs has been reported to be mostly in the ionic form (Ag^+).[9, 42] If CWFs are properly manufactured, the concentration of leached silver in the effluent is less than the WHO guideline for Ag^+ (100 ppb).[9, 47, 48]

4. Impact of water chemistry on CWF performance

Table 3 summarizes the impact that turbidity, natural organic matter (NOM), total dissolved solids (TDS), microbial load, pH, and chlorine have on CWF microbiological removal performance. Previous studies show that an increase in the turbidity and microbial load of the influent solution leads to an increase in LRV.[2, 13, 49, 50] Also, increasing TDS and NOM limits the antimicrobial activity of silver nanoparticles, which reduces toxicity and could lead to an increase in biofilm buildup on the CWF.[41, 51, 52]

Table 3: Effect of water quality parameters on microbial removal by CWFs tested with synthetic solutions

Parameter	Range	LRV (*E. coli*)	Source (LRV)	Current understanding of parameter's effect on microbial removal
Turbidity	8.4 NTU	1.3*	49	Viruses are adsorbed to larger particles and strained out while pore clogging can increase removal of larger microorganisms.[13, 49, 50]
	0.02 NTU	0.31*		
TDS	10 mg/L Mg^{2+}	1.0	51	AgNPs aggregate at higher TDS, which reduces the available surface area and the toxicity.[51, 52]
	1000 mg/L Mg^{2+}	0.7		
Microbial load	10^{10} CFU/100 mL	6.8	2	Larger microbial loads in testing solutions lead to greater measured LRV.[2]
	10^{2} CFU/100 mL	1.7		
NOM	0 mg/L humic acid	0.8	41	NOM coats the AgNPs, minimizing dissolution and the particles' ability to interact with microorganisms.[41, 51]
	5 mg/L humic acid	0.5		

*MS2 bacteriophages

Water chemistry conditions can also affect the long-term performance of CWFs by influencing silver release (Table S3). An increase in the TDS and chlorine concentrations leads to an increase in the silver release from the CWF.[41, 42] An increase in pH and NOM lead to reductions in silver release.[41, 42]

In this review, we categorize testing solutions as natural water or synthetic solutions. 70% of the publications reviewed utilize natural water (collected surface, ground, or rainwater) and

30% use synthetic solutions (deionized water with additives) (Table 1). The water chemistries used in the literature are variable, so a more specific summary of influent chemistries is not feasible. The important water chemistry parameters (turbity, TDS, microbial load, and NOM) for CWF performance (Table 3) are often not reported in the literature, which limits subgroups that could be developed based on water chemistry. In Table S2, we summarize a subset of the papers and provide more detail regarding the influent water chemistry used during testing. This table is an example of the diversity in testing solutions that are used in the CWF literature.

Impact of water chemistry on microbial physiology and quantification

Microbial activity and physicochemical properties are known to be impacted by water chemistry conditions. Selected water chemistry parameters that could affect microbial physiology and removal by CWFs are summarized in Table 4.

Table 4: Potential impacts of water chemistry on microbial physiology and removal with CWFs

Parameter	Effect on microorganisms	Potential effect on LRV	Conditions in CWF studies
Total Dissolved Solids	Cell volume and surface area vary with osmotic pressure[53-56]	Hyperosmotic shock decreases cell volume (up to 40%) and leads to less interaction between bacteria and ceramic, which lowers LRV[53, 57, 58]	High: 200-50,000 mg/L (groundwater) [6, 8-10, 15, 19, 21, 27, 32, 34, 59-64] Low: 10-200 mg/L (surface or rainwater) [7, 8, 11, 12, 16, 18, 19, 26, 38, 43, 44, 65-74] Very low: 0-10 mg/L (DI water) [2, 30, 75]
	Electric double layer (EDL) compression increases interactions between bacteria and other suspended solids and the ceramic matrix[75-77]	Increased ionic strength can lead to higher LRV through the formation of larger flocs or increased interactions with ceramic[75-77]	
Nutrient availability	Cell volume increases with available nutrients [78-82]	Increased cell volume leads to higher LRV[57, 58]	Oligotrophic conditions used in all studies
Quantification method	Cell clusters	For membrane filtration, clusters of cells could be counted as one, lowering LRV[83, 84]	Membrane filtration [2, 6, 7, 9, 10, 12, 15, 18, 19, 21, 26, 27, 30, 38, 43, 44, 59-61, 64, 66, 70, 71, 73, 74, 85]
	Interference from non-target organisms	Most probable number with IDEXX can produce false positives from non-coliform bacteria leading to an increased LRV[86-88]	Most probable number[16, 32, 62, 66, 89, 90]

In CWFs, microorganisms interact with the small, tortuous pores in the matrix of the ceramic filters.[5, 50, 67] Therefore, the volume and surface area of a microorganism impacts the interactions, and subsequent retention, within the ceramic matrix.[57, 58] Previous studies have shown that changing the diameter of microbial surrogates (analogous to virus-, 0.02 μm, through protozoan-sized, 10 μm) changed the log removal of a CWF from 1.5 to 3.2.[57]

Water chemistry can impact a cell by affecting its homeostasis. The intake or release of water from the cell leads to changes in the volume of the cytoplasm and surface area of the cell.[53, 54] Small changes in cell volume due to changing osmotic pressure could have an impact on LRV. A previous study shows that changing the diameter of a spherical particle from 1.0 to 0.5 μm (which is an 87% decrease in volume) can decrease the LRV by 0.5.[57] A 40% reduction in cell volume is possible from changes in osmotic pressure (Table 4).

The effect of osmotic pressure on cell size has implications for the testing of CWFs using surface and groundwater based on the differences in TDS between the two water sources. Surface water has a lower TDS (10-200 mg/L) compared to groundwater (200-50,000 mg/L).[91] Previous studies (Table 4) have used high TDS solutions mimicking groundwater (39%), low TDS solutions similar to surface or rainwater (53%), or very low TDS solutions such as DI water (8%). The size of the bacteria depends on the type and concentrations of the solutes, but it is expected that the increased TDS in groundwater would reduce the cell size compared to bacteria suspended in surface water.[53-56] Therefore, it is possible that the LRV could be lower for CWFs tested with high TDS solutions (groundwater) compared to low TDS solutions (surface water).

The ionic strength of the solution used for testing CWFs also has implications for the charge of the bacteria. Bacteria and other natural surfaces in the environment carry a negative charge, which prevents adhesion of bacteria to other cells and to the CWF.[76, 77, 92, 93] In both cell-to-cell and cell-to-surface interactions, increasing the ionic strength of the solution compresses the electric double layer (EDL), which promotes adhesion.[75-77] Adhesion of cells can lead to the formation of flocs, which are larger and therefore easier to retain in a CWF.[76] Increasing the ionic strength of the testing solution will also promote the adhesion of bacterial cells to quartz, which is the primary mineral in the CWF ceramic matrix.[9, 25, 77] Previous studies have shown that TDS in the groundwater range (>230 mg/L) promotes more adhesion compared to TDS in the surface water and lower range (<45 mg/L).[76, 77] Increased cell-to-cell or cell-to-CWF adhesion could lead to higher LRVs reported in the studies that evaluate CWF microbial removal using groundwater or a solution with similar TDS.

In the environment, most bacteria experience oligotrophic conditions in which a low concentration of nutrients limits cellular growth and size.[78 77, 79, 92] Differences in cell volume can be detected for bacteria grown in nutrient rich environments (nutrients in the g/L range) compared to bacteria in oligotrophic (mg/L bioavailable nutrients) conditions.[79] The concentration of bioavailable nutrients is low in the CWF performance studies reviewed here (Table 4). Bacteria suspended in collected surface, ground, or rainwater to test CWF performance are exposed to natural oligotrophic conditions.[78] Studies with a synthetic testing solution utilize compounds with low bioavailability, such as humic acid (1-10 mg/L)[9, 94] or tannic acid (1-15 mg/L)[34, 95], as the source of natural organic matter for the experiment. Testing conditions in most CWF studies focused on bacterial removal are oligotrophic, so differences in LRV due to cell volume changes because of excess nutrients are likely negligible.

The testing solution used to study CWFs could also affect the technique used to detect and quantify microorganisms. There are three recommended techniques for bacterial quantification during CWF testing: presence/absence, most probable number (MPN), and membrane filtration (MF).[3] MPN and MF are quantitative techniques while presence/absence testing is semi-quantitative.[3] Of the studies that quantified bacteria in order to characterize CWF performance (Table 4), 60% utilized MF, 14% used MPN, and 26% used other techniques (fluorescence imaging, DNA quantification, or plating techniques). MF and MPN have been shown to produce statistically equivalent results and can be applied at CWF factories.[3, 88, 96] The solutions used for CWF performance testing can affect microbial quantification with MF and MPN in different ways. Bacterial quantification with MF assumes that no aggregation of bacterial cells occurs.[83] If clusters of bacteria were to form, this could skew the results, increasing the LRV by causing clusters of cells to be counted as a single colony.[75-77, 83] Aggregation of cells is a more important issue in quantification with MF compared to MPN because MPN is based on the activity of the cell.[88, 96] The aggregation of cells is not likely to be an important issue for laboratory studies that utilize a large microbial load, but could impact the results of studies with a smaller microbial load. Previous studies have used influent bacteria concentrations ranging 10^2-10^{10} CFU/100mL.[2] At lower influent concentrations (such as those found in studies that test CWFs using natural water), bacteria clustering could skew the results. MPN using the IDEXX method can be contaminated with non-coliform bacteria and give false positives in natural water found in tropical environments (a potential issue for the many CWF factories located around the equator).[86-88, 96] Quantification techniques are impacted by the water chemistry conditions, which could influence the final LRV reported.

5. Discussion on standardized performance assessment procedures

As discussed in previous sections, both the manufacturing and testing conditions can affect the performance of CWFs. Previous studies examining the impacts of manufacturing parameters on LRV have shown that CWFs made with smaller grain size clays (such as Red art clay), sawdust, and AgNPs have improved performance compared to larger grained clays (local clays), rice husks, and $AgNO_3$.[11, 15, 26, 27, 39-44] While individual studies have shown the impact of manufacturing parameters on LRV, when the data is aggregated, the impact of the manufacturing variables cannot be decoupled from other variables. In Figure 1 A and B, we summarize LRVs sourced from papers studying the *E. coli* removal performance of silver coated CWFs published between 2009 and 2020 (additional details of these studies can be found in Table S2). This figure does not contain information on the sampling schedule or the method of bacterial quantification (MF vs. MPN). Here, we also simplify the aggregation of water chemistry conditions to two groups: natural and synthetic testing solutions. As mentioned previously, the water chemistry conditions used to test

CWFs are so varied that they cannot be aggregated in any other way. The data summarized in Figure 1 A and B does not show the trends that individual studies have shown previously. When the data is separated into different groups the effect of other manufacture variables were not observed. This is due to the variety of testing conditions that have been utilized to generate the LRV values in each study.

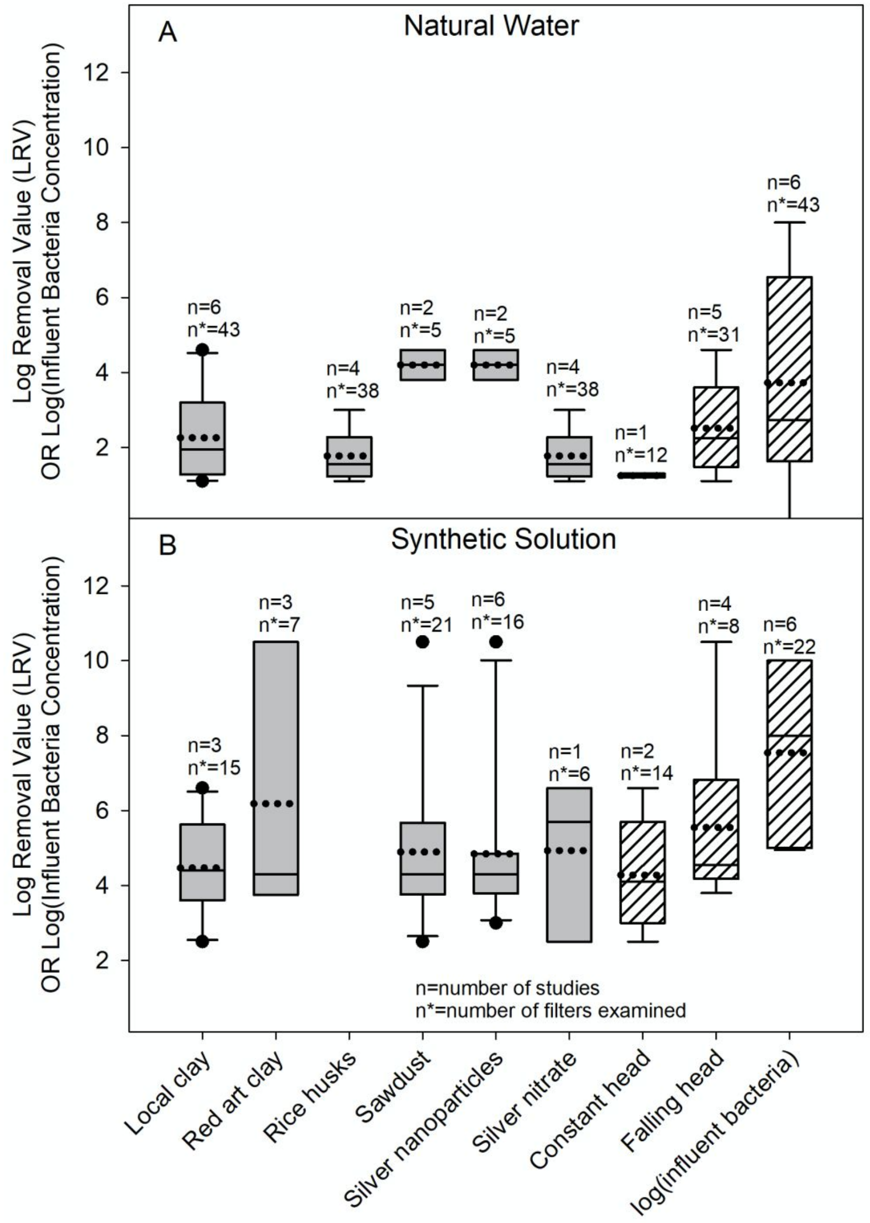

Figure 1: The effect of manufacturing variables (solid gray) and testing conditions (striped) on LRV for CWFs tested with (A) natural water and (B) synthetic solutions. The top and bottom of each box marks the 25th percentile while the whiskers mark the 95th percentile. The mean (dotted line) and median (solid line) are marked within the boxes while dots mark the outliers. The number of studies used to create each box is listed as n and n* is the number of filters used in the studies considered. The studies that have been summarized in Figure 1 have been broken down in greater detail in Table S2.

The data summarized in Figure 1 A and B shows that microbial load could be driving the differences in LRV reported for CWFs tested with natural water and synthetic solution. Figure 1A shows that CWFs tested with natural water have a slightly lower LRV compared to the CWFs tested with synthetic solution (Figure 1B). CWFs tested with a synthetic solution tend to have a larger microbial load (10^4-10^{10} CFU/100 mL)[9, 10, 21, 27, 34, 40] compared to CWFs tested with natural water (1-10^7 CFU/100 mL)[12, 15, 38, 44, 61, 67]. This is supported by Brown *et al,* 2019, which showed that CWFs tested with larger microbial loads have a higher LRV.[2]

Studies using natural water and synthetic solutions should not be used in aggregate comparison analysis since both types of testing conditions have different, important purposes. Natural water conditions are used to determine the effectiveness of CWFs under real conditions and at the user level (Figure 1A).[97, 98] These studies demonstrate the ability of CWFs to remove microbial load to meet drinking water standards.[12, 61, 97] The LRV values reported by studies using natural water could be limited by the lower influent microbial load (compared to the microbial loads in synthetic solutions). Lower microbial loads could lead to the complete removal of bacteria from the filter, which means that the LRV is capped by the microbial load in the influent solution.[2] In studies using synthetic solutions, the high microbial load challenges the filters and a breakthrough of bacteria occurs. Therefore, synthetic solutions are suitable to assess the efficacy of the CWF under controlled conditions. Controlled testing conditions also allows the analysis of the impacts of manufacturing parameters on LRV. However, as the literature stands, controlled laboratory testing of CWF microbial removal has been performed without consensus on the testing parameters. Figure 1 shows that this lack of standardized testing conditions does not allow for comprehensive and systematic comparison of the manufacturing variables on the performance of CWFs and hinders the technological improvement of POU water devices.

A standardized performance assessment could be useful to determine CWF efficacy and highlight the influence of manufacturing differences on the microbial removal performance of CWFs, decoupling the effect of the water chemistry conditions from the testing.[3, 38, 99, 100] CWF manufacturers frequently employ a set of quality control techniques to ensure the quality of their filters before they are sold.[3] These techniques, including visual inspections, acoustic control, and flow rate measurements, are limited because they do not directly measure the microbial removal performance.[3, 34, 39, 49, 85]

There are two standardized performance assessment procedures that have been established for CWFs: one by the United States Environmental Protection Agency (USEPA)[94] and the other by the World Health Organization (WHO)[95]. Table 5 summarizes and compares key points from the USEPA and WHO performance assessment procedures. The USEPA and WHO procedures are each made up of three phases defined by different influent chemistries. The water chemistry conditions for the influent solutions and their potential impacts on LRV are discussed in greater detail in Section 4. Performance metrics (microbial removal, flow rate, etc.) can be evaluated within the framework provided in the protocols.[15, 26] Protocols for microbial cultivation and assay can be found in both documents, ensuring consistent testing. The USEPA and WHO procedures provide direct quantification of microbial removal, unlike flow rate measurement.[9, 94, 95]

Table 5: Summary of USEPA and WHO protocols

		USEPA[94]			WHO[95]		
Testing phases		General	Challenge	Leaching	Conditioning	General	Challenge
Water chemistry conditions	Chorine (mg/L)	0	0	0	N.S.	<0.05	<0.05
	pH	7.5±1.0	9.0±0.2	5.0±0.2	N.S.	7.0±0.5	9.0±0.2
	TOC (mg/L) (Humic acid)	2.55±2.45	>10	1.0	N.S.	1.05±0.95[a]	15±5
	Turbidity (NTU)	2.55±2.45	>30[b]	2.55±2.45	N.S.	<1	40±10[c]
	Temperature (°C)	20±5	4±1	20±5	N.S.	20±0.3	4±1
	TDS (mg/L) (Sea salts)	275±225	1500±150	100	N.S.	275±225	1500±150
	Alkalinity (mg/L as $CaCO_3$) (Sodium bicarbonate)	N/A	N/A	N/A	N.S.	100±20	100±20
Time (days)		13			11		
Performance metrics		Flow rate Turbidity reduction Microbial removal Silver release			Flow rate Turbidity reduction Microbial removal		
Acceptable microorganisms		*Klebsiella terrigena* (ATCC 33257) Poliovirus 1 (LSc) (ATCC-VR-59) Rotavirus Wa (ATCC-VR-899) or SA-11 (ATCC-VR-2018) *Giardia muris* or *Giardia lamblia*			*E. coli* (ATCC 11229) MS-2 coliphage (ATCC 15597-B1) PhiX-174 coliphage (ATCC 13706-B1) *Cryptosporidium parvum oocysts*		
Cultivation methods		Bacteria[101, 102] Viruses[103] Protozoa[104-106]			Bacteria[101, 102] Viruses[107] Protozoa[108]		
Concentration of microorganisms		Bacteria: $\geq 10^7$/100 mL Viruses: $\geq 10^7$/L Protozoa: $\geq 10^6$/L			Bacteria: $\geq 10^5$/100 mL Viruses: $\geq 10^8$/L Protozoa: $\geq 5\times10^5$/L		
Minimum LRV		Bacteria: 6 Viruses: 4 Protozoa: 3			Bacteria: 4 Viruses: 5 Protozoa: 4		
Allowable variance		1 log for each type of microorganism			1 log for each type of microorganism		
Cost (USD/filter)[e]		$59			$65		
Main benefits		Silver leaching phase Higher minimum LRV for bacteria Lower reagent cost			Conditioning phase-less labor intensive Buffers to reach required pH More narrow range for constituents Shorter Modern testing procedures		
Main limitations		Greater time commitment Lower minimum LRV for viruses and protozoa			More expensive (requires more reagents)		

[a] Tannic acid is used instead of humic acid in the WHO protocol.
[b] A.C. Fine Test Dust
[c] ISO spec. 12103-A2 fine test dust
[d] Sea salts
[e] See Table S4 for details
N.S.-Not specified
N/A-Not applicable

6. Discussion of the benefits of standardized performance assessments:

A standardized performance assessment could benefit CWF manufacturers by providing a consistent framework for testing important performance metrics. The USEPA and WHO protocols provide a framework for testing flow rate, turbidity removal, LRV, and silver leaching (in the USEPA protocol).[9, 34, 94, 95] The WHO protocol also includes directions that allow cleaning to occur during testing, which provides some insight into filter reuse.[95] The consistent influent chemistry provides standardization to the testing procedures, which has been severely lacking in the literature. As mentioned previously, the constituents of a testing solution can impact the interactions between a microorganism and the CWF, which can impact the LRV (Table 4). Standardization of the influent chemistry would lead to standardization of the cell size and cell-cell/cell-surface interactions and a more accurate LRV comparison between studies.

The information collected during performance testing would improve CWF performance by assisting CWF manufacturers in selecting raw materials and manufacturing processes that impart a higher performance to the final product.[15, 26, 85] A standardized performance assessment allows manufacturers to accurately compare performance data with other factories.[3, 12, 15, 38] CWF factories can then become more collaborative, sharing practices that can help improve the LRV of the filter. Manufacturers could also use a standardized performance assessment to reach target performance values, such as the minimum LRVs recommended by the USEPA or WHO.[1, 3, 94, 95] Greater standardization in CWF testing allows accurate comparisons between manufacturers or to a standard, such as those proposed by the USEPA or WHO.

The USEPA and WHO procedures also standardize the timing of sample acquisition. The LRV of a CWF changes over time based on several factors, including the saturation and clogging of the pores.[9, 10, 68] The LRV of a CWF can change up to 25-35% during an experiment that lasts

10-12 days.[10, 27] The WHO and USEPA protocols offer a standardized testing schedule that would reduce error that comes from taking samples at different times. This standardization will also help bring consistency to reporting. As the literature stands currently, LRV values are reported based on either the length of time of filter operation or volume of water that was filtered (see Table S2 for examples). Standardizing the way that the timing of bacterial sampling is reported will make comparisons between studies easier.

The studies reviewed showed a lack of stakeholder involvement in the assessment of CWF performance. 90% of the studies reviewed here utilized CWFs or the materials used to construct CWFs from Asia, Central and South America, and Africa. These are areas where CWFs are manufactured and used frequently.[1, 3] However, studies examining CWFs are rarely developed within the communities that manufacture and use them. Figure S1 is a geographic breakdown of the areas where studies on CWFs are developed (based on the contact information for the final author on the paper). Only 17% of the studies that evaluate CWFs have last authors with contact information matching the field study location or the source of the ceramic materials used in testing. A standardized performance assessment could help increase stakeholder involvement by empowering filter manufacturers and local researchers to analyze the performance of CWFs.[100, 109]

While useful, the USEPA and WHO protocols require a significant investment of time and resources (Table 5).[94, 95] The current recommendation is for microbiological quality control to be conducted on a subset of the filters produced.[3] Microbiological quality control testing should be performed on 3 filters from 3 different batches (total of 9 filters) before factory start up and for 0.1% of the filters that will be sold.[3] It is also recommended to perform microbiological quality control whenever there is a change in the burn out/clay/water mixture used in manufacturing or another quality control concern.[3] Ideally, filters should be tested at laboratories local to the manufacturer. The WHO has emphasized the importance of community-level engagement in water, sanitation, and hygiene practices.[110] Sending filters abroad should be reduced as much as possible to incorporate the stakeholders in the process.[100, 109] Some CWF factories already carry out microbiological quality control testing or send filters to be analyzed by local laboratories.[3] Future work in this area should focus on increasing access to microbiological testing for factories. The testing protocols presented in this review have a different objective than the assessment of the technology performed by the WHO for its Member States and United Nations agencies.[111] The USEPA and WHO quality control procedures are designed to be implemented at the manufacturing level and are cheaper and less labor intensive compared to the *Scheme to Evaluate Household Water Treatment Technologies*.[94, 95, 111]

These protocols could be optimized to improve the quality of the data provided.[9, 94, 95] The water chemistry conditions specified in the USEPA and WHO (Table 5) protocols set ranges for the major water chemistry conditions that have been shown to impact LRV (Table 3). The ranges provided in the procedures should be optimized so that they are narrower. For example, the USEPA protocol challenge turbidity requirement is >30. This should be optimized to a more specific range, like the one provided in the WHO challenge water turbidity. A narrower range is easier to reproduce between studies, ensuring consistent testing conditions.

Coordination between factories is an important aspect of the implementation of a standardized performance assessment procedure and sharing the results of that procedure.[1, 3, 12, 38, 49, 85, 99] An internet forum is likely the best way for manufacturers to communicate and share information. This would allow them to post their data and coordinate with research groups or other manufacturers. An internet forum would also increase access to data for modelling studies. CWF factories could post microbial removal data and the accompanying manufacturing processes to the forum. This could be used to develop models studying the relationship between manufacturing variables and microbial removal. Only 8% of the CWF studies reviewed here involved modelling. Greater access to data sets gathered using standardized methods could provide the opportunity for more modelling studies to be performed on CWFs. Appropriate data sharing would allow manufacturers to communicate the processes that improve microbial removal.

7. Conclusion:

A standardized performance assessment procedure for CWFs has the potential to positively impact health in under-served communities worldwide. The performance of CWFs varies depending on the materials used in production and the chemistry of the testing solution. The standardized performance assessments described here could help manufacturers recognize practices that improve the performance of CWFs. Standardization of quality control protocols would highlight the influence of manufacturing parameters on CWF performance. This would lead to the production of higher quality filters and improved health in under-served communities. In this review, we explored the many variables involved in the manufacture and evaluation of CWFs. The application of a standardized performance assessment could assist CWF manufacturers in improving the quality of their CWFs. Standardized performance assessment procedures have the potential to improve health in under-served communities by improving stakeholder involvement and ensuring the development of manufacturing processes that produce high quality CWFs.

Supporting Information:

Supporting information is available for this publication. It includes (1) benefits and limitations of POU drinking water treatment strategies, (2) selection of papers describing the *E. coli* removal of silver coated CWFs, (3) effect of water quality parameters on silver release from CWFs, (4) supporting cost calculations for the performance assessments described here, (5) geographic distribution of the papers produced on CWFs, (6) complete list of references used in this review.

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Conflicts of Interest:

There are no conflicts of interest to declare.

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