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Advancing performance evaluation standards for household water treatment technologies

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ABSTRACT

Diarrheal illnesses and fatalities continue to be major issues in many regions throughout the world. Household water treatment (HWT) technologies (including both point-of-use (POU) and point-of-entry (POE) treatment solutions) have been shown as able to deliver safe water in many low-income communities. However, as shown herein, there are important inconsistencies in protocols employed for validating performance of HWTs. The WHO does not stipulate influent concentration as a parameter that could influence removal efficacy, nor does it indicate an influent concentration range that should be used during technology evaluations. A correlation between influent concentration and removal is evidenced herein ($R^2 = 0.88$) with higher influent concentrations resulting in higher log-removal values (LRVs). The absence of a recommended standard influent concentration of bacteria (as well as for viruses and protozoa) could have negative consequences in intervention efforts. Recommendations are provided that regulatory bodies should specify an influent concentration range for testing and verification of HWT technologies.

Key words | ceramic water filters (CWFs), diarrheal disease, drinking water treatment, household water treatment (HWT), point-of-entry (POE), point-of-use (POU)

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ABBREVIATIONS

CWF	Ceramic water filter
HWT	Household water treatment
LRV	Log removal value
POU	Point-of-use
POE	Point-of-entry
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

INTRODUCTION

The current state of water safety

Diarrheal illnesses and fatalities are prominent issues in many regions of the world (Harvey *et al.* 2015). Among the world's populations where poverty is most severe, diarrheal diseases are the second leading cause of death (WHO 2017). Diarrheal diseases were the cause of an estimated 1.39 million deaths in 2016 (WHO 2017), and are among the leading causes of death among children under five years of age (UNICEF 2012; WHO 2016).

Approximately 90% of diarrheal deaths can be attributed to inadequate drinking water quality, sanitation, and hygiene (Black *et al.* 2003). Hence, improved delivery of safe water is required for those in the world who rely upon drinking water sources with fecal contamination – currently, about one in four members of the global population (WHO 2014). According to bacterial fecal indicators, more than 1.1 billion people consume water with at least moderate risk of disease (WHO 2014). Bacterial,

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viral, and protozoan species are the primary sources of diarrheal illness (Gall *et al.* 2015). It is in this context that researchers, international organizations, governments, and non-governmental organizations strive to develop low-cost water treatment technologies and programs with the goal of providing safe drinking water to low-income populations.

Household water treatment technologies

An effective method to improve drinking water safety for low-income populations is to promote utilization of point-of-use (POU) or point-of-entry (POE) treatment technologies (e.g., Quick *et al.* 1999; Mintz *et al.* 2001; Clasen & Mintz 2004; Abebe *et al.* 2014; Clasen 2015), which are collectively referred to as household water treatment (HWT) technologies. POU treatment is implemented directly before consumption, while POE technologies treat water where it enters the household. These household treatment options are conventionally paired with solutions for safe household water storage.

HWT technologies are considered important as interim and immediate solutions for communities where centralized treatment is difficult, expensive, or infeasible (Mintz *et al.* 2001; Zwane & Kremer 2007). They can also be effective in households with intermittent water supplies (Bivens *et al.* 2017), or as temporary solutions in humanitarian crises (Martin-Simpson *et al.* 2015; Ramesh *et al.* 2015). There are several household treatment technology interventions that have been proven to significantly reduce the frequency of diarrheal occurrence (Reller *et al.* 2003; Crump *et al.* 2005; Enger *et al.* 2013; Abebe *et al.* 2014). However, there is a large degree of variation in reported effectiveness of HWT solutions between studies (Hunter 2009).

For HWT technologies to be considered appropriate and potentially effective for low-income and marginalized segments of the world's population, robust technology evaluation standards are needed. The standards must be capable of demonstrating attainment of treatment levels which provide water that sufficiently reduces the risk of waterborne illness. Analysis of HWT interventions has indicated that ceramic water filters (CWFs) are superior to biosand filters, chlorine, and safe water storage, and coagulant-chlorine HWT technologies (Hunter 2009).

Ceramic water filters

CWFs are porous, clay-based filtration devices that retain microbiological pathogens through physical size exclusion and the development of a protective biofilm. CWFs are low cost and are easily manufactured with minimal capital investment. The combination of these factors enables utilization of CWFs in many developing regions (van Halem *et al.* 2009; Ren *et al.* 2013; Mellor *et al.* 2014).

Typical log removal values (LRVs) of *Escherichia coli* and other bacterial species are reported between two and four (Abebe *et al.* 2015; Mikelonis *et al.* 2016), although some publications have reported LRVs between five and seven (van Halem *et al.* 2007; Rayner *et al.* 2013; Yakub *et al.* 2013). Variations in reported CWF bacterial removal efficiencies indicate potential inconsistencies in test protocols between studies. Additionally, concerns have been raised about CWFs' ability to protect end-users from viruses (Farrow *et al.* 2014) and chemical contaminants such as nitrates (Murphy *et al.* 2010). Other persistent deficiencies of CWFs include relatively poor performance in the field (in contrast to laboratory studies) (Farrow *et al.* 2018), and an excessive rate of permanent fouling (van Halem *et al.* 2009; Salvinelli *et al.* 2016).

CWF performance has been reported as impacted by variations in design parameters (e.g., pore size, porosity, silver impregnation) (Muhammad *et al.* 2009; Murphy *et al.* 2010; Mwabi *et al.* 2011; Simonis & Basson 2011; Brown *et al.* 2012; Rayner *et al.* 2013; Abebe *et al.* 2015; Rayner *et al.* 2016; Pérez-Vidal *et al.* 2016) as well as test methodologies. For example, it is unclear whether silver impregnation significantly improves pathogen removal. Current literature regarding the impact of silver impregnation on CWF bacterial removal efficacy is inconsistent (Fewtrell 2014); some publications suggest that silver impregnation improves performance (Oyanedel-Craver & Smith 2008; Wubbels *et al.* 2008; Kallman *et al.* 2011; Mikelonis *et al.* 2016), while others indicate no significant difference between filters with, and without, silver impregnation (Brown & Sobsey 2010; Clark & Elmore 2011; van Der Laan *et al.* 2014).

Guidelines for household water treatment (HWT) technologies

Drinking water treatment technologies must be carefully evaluated before they are used as an intervention technology. Governmental and international organizations have provided frameworks by which household treatment technologies should be evaluated. Publications from the World Health Organization (WHO), United States Environmental Protection Agency (USEPA), and NSF International are commonly relied upon.

World Health Organization

The WHO *Guidelines for Drinking-Water Quality* (WHO 2011a) lists factors that may affect microbiological removal efficacy of HWT technologies. These factors include flow rate, pore diameter (for permeable filtration technologies), and the presence or absence of chemical additives. The WHO also published a document entitled *Evaluating household water treatment options* (WHO 2011b), which recommended baseline log removal values (LRVs) of microbiological contaminants that should be achieved by any HWT solution. Two classes of protectiveness were proposed: 'highly protective,' which requires four log removal of the bacterium *Campylobacter jenuni*, five log removal of rotavirus, and four log removal of the protozoan *Cryptosporidium*; and 'protective,' which relaxes the minimum LRVs to two, three, and two, respectively. These target LRVs are based on quantitative microbial risk assessment (QMRA) methods using initial pathogen concentrations that would typically be found in untreated wastewater. In *Evaluating household water treatment options*, parameters that are described to affect the removal performance of a POU technology include turbidity, temperature, flow rate, and operating and cleaning protocols, among others. Notably, neither of the WHO documents mention influent concentration as a parameter that could influence removal efficacy, nor do they stipulate an influent concentration range that should be utilized during technology evaluations.

NSF International and USEPA

The NSF standard protocol for household treatment technologies (NSF International n.d.) is based on a USEPA report entitled *Guide Standard and Protocol for Testing Microbiological Water Purifiers* (USEPA 1987). The USEPA report presented more stringent LRVs for each class of microbiological contaminants: six for bacteria (*Klebsiella terrigena*), four for viruses (poliovirus and rotavirus) and three for protozoa (*Giardia*). In contrast to the WHO documents, the USEPA stipulated influent concentrations to be used for each contaminant class. The standard influent bacterial concentration for technology verification is 10^7 CFU/100 mL.

Performance evaluation of ceramic water filters

Across the literature, there is a lack of consistency in the influent *E. coli* concentrations employed for testing CWFs. A wide range of concentrations has been utilized, ranging from 1.2×10^2 to 9.9×10^8 CFU/100 mL (Bielefeldt *et al.* 2009; Muhammad *et al.* 2009; Murphy *et al.* 2010; Mwabi *et al.* 2011; Simonis & Basson 2011; Brown *et al.* 2012; Rayner *et al.* 2013; Yakub *et al.* 2013; Abebe *et al.* 2015; Matthies *et al.* 2015; Pérez-Vidal *et al.* 2016). Of 30 publications evaluating CWF removal of *E. coli*, only 11 included data sufficient to determine both log removal value (LRV) and influent *E. coli* concentration (Bielefeldt *et al.* 2009; Muhammad *et al.* 2009; Murphy *et al.* 2010; Mwabi *et al.* 2011; Simonis & Basson 2011; Brown *et al.* 2012; Rayner *et al.* 2013; Yakub *et al.* 2013; Abebe *et al.* 2015; Matthies *et al.* 2015; Pérez-Vidal *et al.* 2016). The data from these publications is plotted in Figure 1. It is of note that the included studies utilized CWFs with different design features, pore diameters, silver content, and challenge water characteristics. Regardless of the significant differences between the CWFs, the data set suggests a log-log relationship between removal value and influent concentration ($R^2 = 0.75$).

Research goals

While a log-log relationship is evident in Figure 1, results are inconclusive due to the variable CWF characteristics and test methods employed in the individual studies. Only one publication that reported influent concentration as a significant factor in the resultant LRV of an HWT could be identified (He *et al.* 2018), and the authors did not

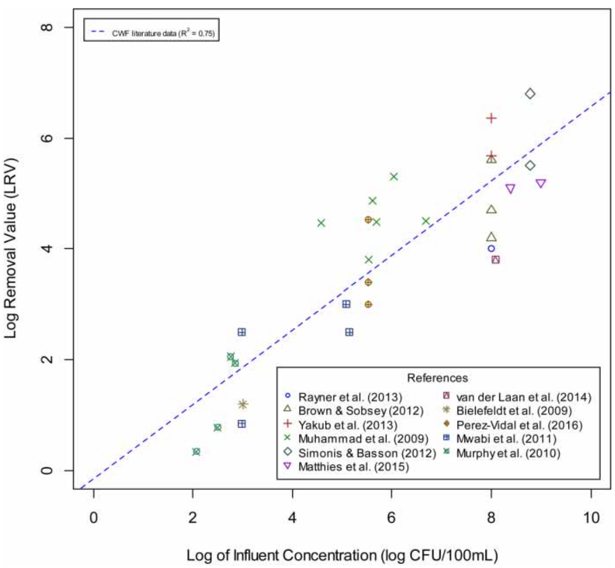

Figure 1 | Influence of influent concentration on log removal value (LRV): literature data.

thoroughly discuss the resulting implications. Therefore, a laboratory study using replicate CWFs was conducted to determine whether the log-log relationship could be confirmed.

METHODS

Laboratory analysis

Column-shaped CWFs (Figure 2) were obtained from an NGO that manufactures and distributes CWFs in rural southeast Asia. The tests using these filters involved soaking in deionized water for 48 hours before testing to ensure the pores were fully saturated, and to prevent airborne contamination. Each filter was flushed with deionized water for 48 hours, after soaking, to remove debris and air that would prevent water from permeating through the internal pore structure. Each filter was flow-tested to ensure factory specified flow-through rates of 1 to 3 L/h (the flow rate range used by the NGO for quality control). Filters with flow-through rates outside of this range were not investigated.

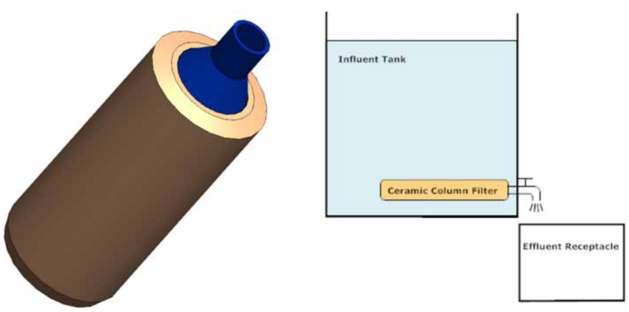

Figure 2 | Ceramic column filter apparatus.

E. coli challenge tests at concentrations ranging between 3.4×10^2 and 9.4×10^9 CFU/100 mL were conducted. All samples were analyzed following EPA Method 1603 (Method 1603: *Escherichia coli* (*E. coli*) in water by membrane filtration using modified membrane-thermotolerant *Escherichia coli* agar). For each trial, deionized water was drained from the tank until the water level reached approximately 5 cm above the top of the filters. The bacterial spike was then dropped via pipette into the water at multiple locations to approach an even distribution of bacteria. Deionized water was subsequently added until the desired water level for the trial was reached, with the inlet hose placed at an angle such that it aided in circulating the water and stimulating an even distribution of bacteria throughout the water volume. When the desired water level was obtained, filtration was allowed to occur undisturbed for 2 hours (±15 minutes) to reach equalized conditions. Influent and effluent samples were collected, and flow rates for all filters were measured in triplicate. Each sample dilution was analyzed in triplicate. Method blanks were employed during each bacterial assay (as stipulated in EPA Method 1603).

RESULTS AND DISCUSSION

A correlation between influent concentration and removal is evident ($R^2 = 0.88$) (see Figure 3). As is apparent in Figure 3, higher influent concentrations result in higher LRVs. Lower challenge concentrations yielded LRVs between three and four. The degree of variability observed during laboratory trials is estimated from data at influent concentrations ranging from 5.35 to 5.68 log CFU/100 mL ($n = 23$). The average influent concentration within this range was 5.54 log CFU/100 mL. The average log removal is observed to be 4.14 LRV (standard deviation = 0.33 LRV) within this range. The log-removal data do not show any evidence of non-normality utilizing the Shapiro–Wilk test ($p > 0.05$)

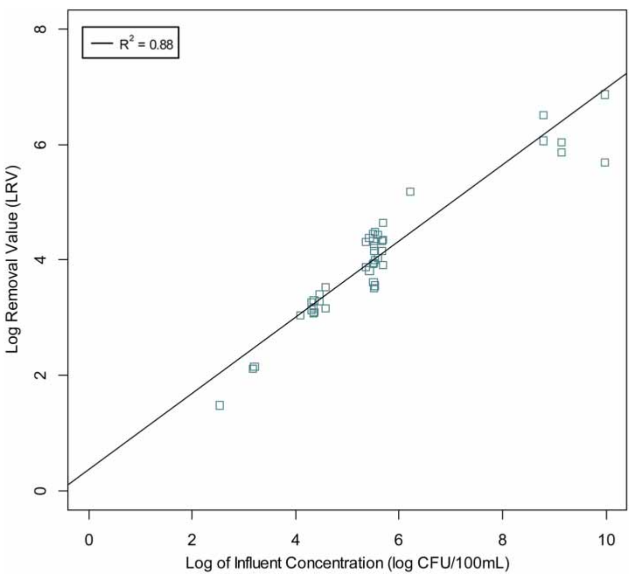

Figure 3 | Influence of influent concentration on log removal value (LRV): laboratory data.

(McBean 2019). Therefore, the fraction of organisms passing through the filter is log-normally distributed.

Literature data and data obtained in this research indicate a similar trend, as illustrated in Figure 4, with a strong correlation between influent concentration and removal efficiency. Therefore, important modifications to the WHO standards for evaluation of household treatment technologies are required.

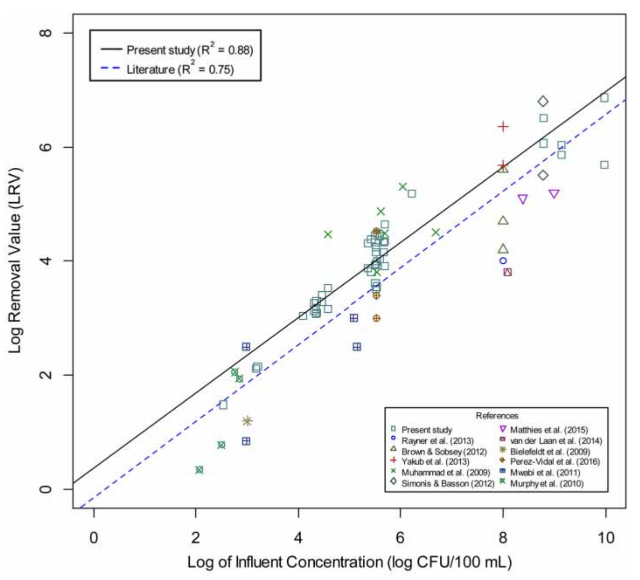

Figure 4 | Influence of influent concentration on log removal value (LRV): comparison of laboratory and literature data.

Implications for CWF regulation

WHO specifications do not provide sufficient guidance for the evaluation of HWT technologies. The absence of a recommended standard influent concentration of bacteria (as well as for viruses and protozoa) could have negative consequences in intervention efforts. To illustrate the potential downfalls, consider a development worker who is not well educated in water science, yet wishes to have a CWF's bacterial removal efficacy evaluated. This evaluator may very well solely consider the WHO standards, without being aware of the NSF or USEPA documents' existence. If this were the case, then the evaluator would operate on the assumption that an LRV should be achieved for the technology to be considered protective, but would not have any basis for choosing a bacterial challenge concentration; the problem is that the evaluator might then select nearby surface water as challenge water. Since surface water typically has low *E. coli* concentrations (typically less than 10^4 CFU/100 mL), and thus, from the findings reported herein, LRVs higher than three would not be expected (which is below the WHO's 'highly protective' benchmark for bacteria). Therefore, technology verification using surface water, regardless of the veracity of the CWF in question, would inevitably result in a relatively low LRV and thus not reach the 'highly protective' WHO standard. The same conclusion applies to those who would choose low concentrations for challenge water.

It is evident from Figure 4 that the lack of provision of 'standard' challenge concentrations could lead to misinterpretation of results. Without a recommended concentration to be paired with the required LRVs (as provided in the NSF and USEPA documents), technology evaluators are free to select influent concentrations arbitrarily, meaning resultant LRVs are also arbitrary.

These findings indicate that the WHO testing protocols should be revised to include standard influent concentrations to accompany recommended LRVs.

Implications for ceramic water filters

As evident from Figure 1, there has been a wide range of *E. coli* challenge concentrations across the literature (with many studies (63% of publications reviewed) not reporting challenge concentrations). In many cases, publications do not include justifications for the challenge concentrations employed in the evaluation. Due to variations in challenge concentrations across the literature, the comparison between publications is difficult.

There are some studies which demonstrate awareness that challenge *E. coli* concentration influences LRVs. These include: Farrow *et al.* (2018), who cited low influent concentrations as a potential differentiating factor between laboratory trials and field trials involving CWFs; and van Halem *et al.* (2007), who reported what was called the 'maximum log removal' of a CWF by using a high influent concentration (which was left unreported). Farrow *et al.*'s analyses revealed that significantly lower LRVs are consistently found in end-user field evaluation studies as opposed to laboratory studies. This finding has been corroborated by other publications (e.g., Murphy *et al.* 2010). Typical explanations for the variation in laboratory and field studies include insufficient operator knowledge and lack of access to protective sanitation; the recommendations for improvement, then, relate to improved designs that compensate for lack of operator expertise and adequate sanitation. End-user/field studies exclusively use challenge waters of relatively low concentrations. Therefore, an influential variable and differentiating factor between laboratory and field studies is challenge/source water concentration. In fact, the WHO recommended LRV of four (for bacteria) is difficult to obtain in field studies, irrespective of the technology (where the influent concentration is typically under 1,000 CFU/100 mL).

CONCLUSIONS

When evaluating the microbiological removal performance of CWFs, source water concentration has a significant impact on removal efficiency, with higher source water concentrations resulting in higher LRVs. The results presented herein strongly indicate that researchers should henceforth consider influent concentration as an important parameter in HWT bacterial removal studies. A similar log-log relationship (between removal value and influent concentration) would be expected for many microbiological contaminant classes (viruses, bacteria, protozoa) and filtration devices, including CWFs, slow sand filters, and membrane filters.

The WHO's standards for evaluation of household drinking water treatment (HWT) devices need to be modified to include standard challenge microbiological concentrations. Without these clarifications, the potential remains for misinterpretation of results, which poses an avoidable threat to water safety and public health. Further, researchers and policy-makers need to take into account the challenge concentrations employed in previous studies when evaluating/comparing the bacterial removal efficiency of any HWT technology.

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