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3 AUTHORS:

Dianjun Ren
University of Virginia

Lisa M Colosi
University of Virginia

James Albert Smith
University of Virginia

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Evaluating the Sustainability of Ceramic Filters for Point-of-Use Drinking Water Treatment

Dianjun Ren, Lisa M. Colosi,* and James A. Smith

Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, Virginia, 22904 United States

Supporting Information

ABSTRACT: This study evaluates the social, economic, and environmental sustainability of ceramic filters impregnated with silver nanoparticles for point-of-use (POU) drinking water treatment in developing countries. The functional unit for this analysis was the amount of water consumed by a typical household over ten years (37,960 L), as delivered by either the POU technology or a centralized water treatment and distribution system. Results indicate that the ceramic filters are 3–6 times more cost-effective than the centralized water system for reduction of waterborne diarrheal illness among the general population and children under five. The ceramic filters also exhibit better environmental performance for four of five evaluated life cycle impacts: energy use, water use, global warming potential, and particulate matter emissions (PM10). For smog formation potential, the centralized system is preferable to the ceramic filter POU technology. This convergence of social, economic, and environmental criteria offers clear indication that the ceramic filter POU technology is a more sustainable choice for drinking water treatment in developing countries than the centralized treatment systems that have been widely adopted in industrialized countries.

1. INTRODUCTION

Lack of access to safe, reliable water sources remains a critical problem for millions of people worldwide, especially in the developing world. The United Nations and the World Health Organization (WHO) estimate that 780 million people (roughly 11% of the world's population) were without access to an improved water supply as of 2012.[1] As such, waterborne diseases such as diarrhea, cholera, enteric fever, and hepatitis cause 1.6 million deaths annually, and children under five years old are especially vulnerable.[2] Thus, there is a great need for technology and infrastructure capable of providing clean drinking water in economically depressed regions.

Point-of-use (POU) water treatment devices are one appealing option for expanding access to clean water in developing countries via "decentralized" water treatment, whereby individual households treat their own drinking water before consuming it. This is in contrast to "centralized" water treatment systems, wherein water is treated at one central location and then distributed via pipes to households for consumption without any additional treatment. In a recent review, the WHO concluded that point-of-use water treatment technologies constitute simple, socially acceptable, and low-cost interventions with significant potential to reduce global waterborne disease and death.[3] In a follow-up meta-analysis, Clasen et al.[4] found that water interventions at the individual household level are more effective in improving water quality, and by extension reducing diarrheal illness, than source-level interventions and that they may be more cost-effective over time than centralized systems. These findings are especially compelling given the dramatic growth in the accessibility of piped water within individual household premises, from 45% of the global population in 1990 to 54% in 2010.[1] Ready access to piped water, though not necessarily treated water, presumably increases the appeal of point-of-use water treatments. Thus, it is worthwhile to examine point-of-use treatment technologies in depth.

Silver-impregnated ceramic water filters are one particularly promising type of POU water treatment technology.[5] This technology has been shown to effectively remove microorganisms (e.g., *Escherichia coli*, total coliforms, protozoan oocysts) and turbidity from water during extensive laboratory testing and field testing with actual household consumers.[6−10] Recent work has focused on assessing the cultural acceptability of this treatment among its intended users, understanding the impacts of raw water quality on disinfection performance, and varying materials composition and/or manufacturing techniques to optimize disinfection.[9,11] The results of these studies are generally positive; therefore, it is promising that nongovernmental agencies such as Potters for Peace, PureMadi,

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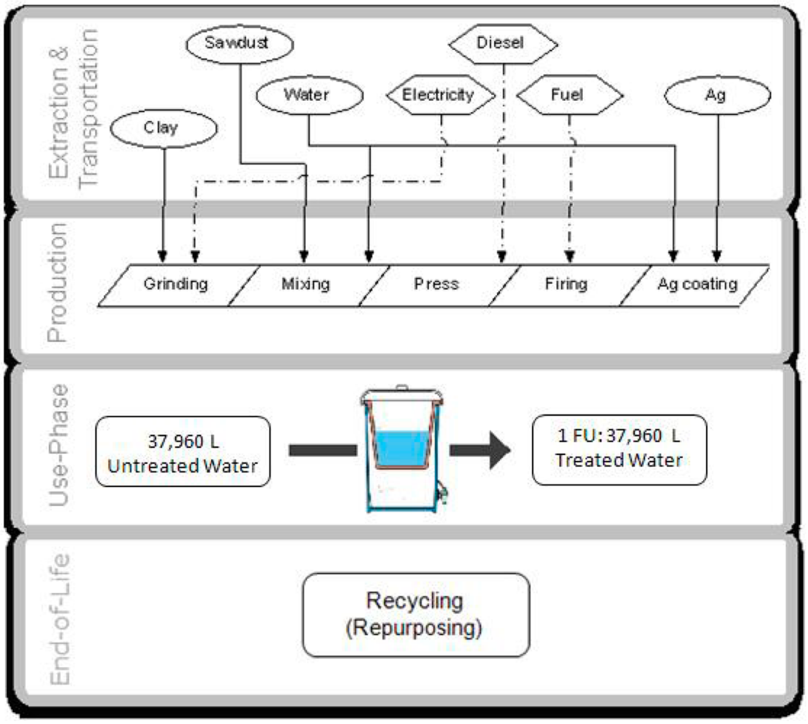

Figure 1. System boundaries for the ceramic filter POU LCA. Life cycle stages are shown from top to bottom. Ovals depict raw materials inputs, and hexagons depict energy inputs.

and FilterPure have successfully established more than 35 filter factories worldwide to produce the filters using local labor and predominantly local materials (i.e., clay and combustible matter such as sawdust or flour).[12]

This study used the framework of the "triple bottom line" to assess the overall sustainability of silver-impregnated ceramic filters for POU water treatment in developing world communities. The three elements of the triple bottom line are social sustainability, environmental sustainability, and economic sustainability; thus, we evaluated the ceramic filter technologies from each of these perspectives, using different metrics for each. We also evaluated a centralized water treatment and distribution system, to enable comparison between both treatment options. Because some inputs required for calculation of the selected metrics are location dependent, we used some data from South Africa for this analysis; however, it is expected that the results could be generalized for other developing world countries. To our knowledge, this is the first comprehensive sustainability assessment for the ceramic filter technology.

2. METHODOLOGY

We evaluated ceramic filter POU water treatment devices based on their social, economic, and environmental performances. A different metric was used to assess each criterion. All metrics for both systems, the ceramic filters and the benchmark were calculated in spreadsheet format using Crystal Ball. This software suite facilitates Monte Carlo analyses by allowing users to define statistical distributions for input parameters and then automating a user-defined number of sampling trials (100,000 in this study). It then generates distributions of selected output parameters, for use in assessing uncertainty and sensitivity.

The POU ceramic water filter and the centralized water system were both evaluated on the basis of their ability to deliver the so-called "functional unit" (FU), which was defined as the amount of water consumed for drinking by a "typical" developing-world household over ten years. The assumed household size was 5.2 persons, arising from the average of 5.6 persons per household in Near East/North Africa, 5.1 in Asia, 5.3 in sub-Saharan Africa, and 4.8 in Latin America.[13] Assuming 2 L/d per person for drinking water,[14] the total amount of water consumed over 10 years is roughly 37,960 L.

2.1. Evaluating Social Sustainability. The key *social* metric was efficacy of reduction in waterborne diarrheal illness, based on previously published studies, as quantified using disability adjusted life years (DALYs). This is a commonly used metric that accounts for the amount of productive time (in years) lost due to illnesses or deaths associated with a particular disease. There are two components: years of life lost (YLL) and years of life lived with disability (YLD). These correspond to mortality and morbidity, respectively. Equations 1 and 2 summarize the calculation of how many YLLs and YLDs from diarrhea could be averted following implementation of the ceramic filters as a POU water treatment.[15]

$$\mathrm{YLD} = (1 - \mathrm{CFR}) \times N \times E \times \mathit{Eff} \times \mathrm{Weight} \tag{1}$$

$$\mathrm{YLL} = \frac{\mathrm{CFR} \times \mathit{Eff} \times N}{r} \times (1 - \mathrm{e}^{-r \times \mathrm{LE}}) \tag{2}$$

where CFR is case-fatality rate; i.e., the percentage of persons dying from diarrhea once they have contracted it. CFR values for the general population (0.04−0.12%) and children under five (0.15%) were collected from previously published literature.[16−18] A CFR value for individuals with human immunodeficiency virus (HIV) (7%) was taken from previously published literature.[19] *Eff* is the effectiveness of the selected intervention in mitigating diarrhea, as expressed using a percentage. This parameter was computed on the basis of results from numerous field studies, as summarized in Section

1.1 of the Supporting Information (SI). N is the number of people in a typical household (5.2). E is the duration of illness per person per year: 0.077 year for the general population or 0.074 year for persons with HIV.[20−22] Weight is an empirical factor assigned to the days on which a person experiences diarrhea, as a way of accounting for impairment in quality of life. A value of 0.11 was used in this study.[23] r is an empirical parameter which assigns a quality of life premium for years lived at younger ages compared to years lived at older ages. A discount rate of 3% was used for this study.[15] Finally, LE is the typical life expectancy for the local population: 49.3 years for the general population or 34.0 years for individuals with HIV.[19]

The YLD and YLL quantities from eqs 1 and 2 are summed together to compute DALYs per year. This annual quantity is then integrated over some time duration (t) of interest, as shown in eq 3. The duration for this study was 10 years, based on the selected functional unit.

$$\text{Total DALYs} = \sum_{t=0}^{10\text{ years}} \frac{(\text{YLD} + \text{YLL})}{(1+r)^t} \tag{3}$$

We computed the quantity of DALYs that could be averted for the general population, children under five, and adults with HIV. These groups have different vulnerabilities to diarrheal illness.

2.2. Evaluating Economic Sustainability. The key *economic* metric was cost-effectiveness, which combines the price per FU with the efficacy of diarrheal prevention metric referenced in Section 2.1. These two parameters are combined into a ratio, with price as numerator and efficacy as denominator, similar to "cost effectiveness" ratios described by the World Bank in 1993 and later revised by the World Health Organization.[15] The retail price per filter was based on data from a survey by Rayner et.al,[12] accounting not only for the cost of raw materials but also for capital investment, maintenance and reinvestment, and marketing, all of which are essential to sustain a functioning ceramic filter factory. The time value of money over the 10-year span encompassed by the FU was accounted for with a 5% discount rate.

2.3. Evaluating Environmental Sustainability. There were five environmental metrics: net energy consumption per FU (in MJ), net global warming potential per FU (in kg CO_2-equivalent), net water usage per FU (in m^3), smog potential per FU (in g NO_x-equivalent), and particulate matter emissions per FU (in g PM10, comprising particles with diameters less than 10 μm). These quantities were computed using life cycle assessment (LCA). This is a systematic accounting of all impacts associated with a process or product throughout all stages of its life cycle: from extraction of raw materials, through materials processing, manufacturing, distribution, use and maintenance, and ultimately disposal or recycle at the end of its useful life. Figure 1 shows the system boundaries for the ceramic filter LCA that were included in this study, identifying the necessary materials and energy inputs required to produce each filter and also identifying the subprocesses which make up the manufacturing (i.e., production) stage. Life cycle data for the materials and energy inputs corresponding to production of as many filters are required to deliver the FU were taken from the ecoinvent database.[24] Section 2.2 of the SI provides full details about the LCA procedures used for the ceramic filter.

2.4. Benchmarking Analysis. The social, economic, and environmental metrics from Sections 2.1, 2.2, and 2.3, respectively, were also computed for a typical centralized water distribution system in South Africa. This system performs the following functions: collection and impoundment of raw water, treatment of raw water to potable quality, and distribution of potable water. We assumed that surface water from an aboveground reservoir (i.e., dam) is used as the raw water and that the treatment train consists of coagulation−flocculation−settling, granular filtration, granular activated carbon (GAC) absorption, and chlorination for disinfection.[25] These burdens were scaled to account for production of just 1 FU (37,960 L), even though centralized systems typically create much larger volumes of treated water for drinking and other uses. Finally, because environmental burdens of a centralized water system are accrued mostly during the operation (use) phase (typically 60−70 years), construction and decommissioning burdens were excluded from the benchmark LCA analysis.[26] Sections 1.2 and 2.3 of the SI provide additional details about calculation of the social/economic and environmental (LCA) metrics, respectively, for the centralized water system.

3. RESULTS AND DISCUSSION

3.1. Social Sustainability. With respect to social performance, the most desired outcome for any water treatment system is sustained prevention of waterborne illness. Thus, our first task was evaluating the ceramic filter's ability to reduce diarrheal illnesses and deaths in three groups of interest: the general population, children under five, and adults with HIV. The efficacy of the filters was quantified using DALYs, as summarized in eqs 1−3 and Section 1.1 of the SI. The values of CFR and *weight* arose from selection of diarrhea as the target illness. Similarly, the values for N and LE arose from selection of South Africa as the location of interest. r was fixed by standard convention. Thus, *Eff* was the most informative parameter for calculating what reduction of DALYs could be achieved by the ceramic filter POU technology or the centralized system.

Eff values for silver-impregnated ceramic filters were taken from previously published field tests. Clasen et al.[27] reported that silver-impregnated ceramic filters reduced diarrheal incidence by 64% among the general population and by 71% among children under five, for a Bolivian community; though, the geometry of the filter apparatus used in Clasen's study was not identical to that of the technology that is the focus of this study. A similar study in Cambodia reported 46% reduction for the general population and 48% reduction for children under five.[28] These data were assigned to input distributions for *Eff* in both populations. The resulting values for DALYs averted per FU by the use of the ceramic filter technology were 0.71 year for the general population and 0.14 for children under five. The breakdown of DALYs for the general population was 0.50 years of life lost (YLL; i.e., mortality) plus 0.21 years of life with disability (YLD; i.e., morbidity) for a typical household over ten years. Correspondingly, the DALY breakdown for children under five was 0.11 YLL plus 0.02 YLD. These and all DALY quantities computed for this study are summarized in Table 1.

The ceramic filters were also evaluated for their effectiveness in reducing waterborne diarrheal illness among adults with HIV. This is of great relevance because HIV-positive individuals make up an appreciable percentage of the population in many developing countries (e.g., roughly 30% in South Africa since 2008[1]), and persons with HIV are especially vulnerable to waterborne illness.[22,29] Diarrhea is one of the most frequent ailments of HIV-positive persons in resource-limited countries.[30,31] Raw data for estimation of the *Eff* parameter were

Table 1. Summary of DALY Results for Two Water Treatment Interventions (POU Ceramic Filter and Centralized Water Treatment System), for Three Populations of Interest: General Population ("General"), Children under Five Years Old ("Children"), and Adults with HIV Receiving Standard Antiretroviral Therapy (ART)[a]

	ceramic filter POU			centralized water system	
	general	children	HIV	general	children
YLD per year	0.024	0.003	0.001	0.017	0.004
YLL per year	0.059	0.013	1.834	0.040	0.016
DALY per year	0.083	0.016	1.835	0.057	0.020
YLD total	0.207	0.025	0.011	0.141	0.031
YLL total	0.502	0.112	15.645	0.342	0.140
DALY total	0.709	0.136	15.656	0.484	0.171

[a]YLD is "years of life with disability"; YLL is "years of life lost". "YLD total", "YLL total", and "DALY total" refer to the ten-year period specified by the functional unit, assuming a discount rate of 3%.

taken from a field study of persons with HIV receiving standard antiretroviral therapy (ART) in Limpopo Province, South Africa and using ceramic water filters.[32] The average value of *Eff* for the POU device was 79%. This translates to 15.5 DALYs averted (15.5 YLL and 0.02 YLD) over ten years.

Eff values for the centralized water treatment system were also taken from published studies on centralized water distribution in the developing world. Bahl et al.[33] reported the risk of diarrhea contraction to be 63% for consumption of piped water in Zambia. Wang et al.[34] reported a similar value of 62% for consumption of piped water in a Chinese community. These values were converted into effectiveness via subtraction from 100%, such that *Eff* for the general population was roughly 37.5%. A previously published review of 67 studies found that centralized water systems reduce childhood diarrhea by 21−30%;[35] thus, *Eff* was roughly 26% for children under five. These values are lower than *Eff* values for centralized water systems in the US or Europe; however, lack of proper management and recontamination during distribution are known to adversely impact water quality for systems in developing countries.[35,36] The resulting DALY reductions for the benchmark system were 0.48 per household for the general population and 0.17 per household for children under five. The breakdown was 0.34 YLL plus 0.14 YLD for the general population and 0.14 YLL plus 0.03 YLD for children under five. These values are lower than what was reported for the ceramic filter POU technology, consistent with previous studies in which children with access to piped water were found to have higher diarrheal incidence than children without access to piped water.[36,37]

The ceramic filter POU technology offers additional social sustainability benefits, compared to the centralized system, that are less easily quantified than DALY reduction. For one, field testing indicates that the filters offer good cultural acceptance, by virtue of their convenience and health benefits.[9] They also offer good robustness and resiliency compared to the centralized system, because there is less likelihood of post-treatment recontamination during normal operation and the risk of widespread service disruption following natural disasters is significantly reduced. Finally, the use of local materials and labor to produce the filters gives the community a sense of ownership over the technology and also renders the filter factory enterprise a vehicle for stimulation of the local economy.[38] In contrast, centralized water treatment and distribution systems are so capital-intensive that their construction in developing countries must be financed or subsidized by outside entities, such as the World Bank.[39]

Having quantified and/or articulated the possible social sustainability *benefits* associated with use of the ceramic filter POU and its benchmark system, it was then necessary to compute what economic and environmental *costs* could arise from use of either option. A *sustainable* water system should deliver safe water without engendering undue environmental burdens or economic costs. Thus, cost−benefits ratios were computed for both systems and compared to each other.

3.2. Economic Sustainability. The most immediate indicator of economic sustainability for each evaluated water treatment technology is the direct cost to the consumer for delivery of one FU. For the ceramic filter, it was first necessary to compute how many filters would be required to deliver the FU over 10 years. Taking into account filter lifetime (∼3.5 years[6,7,40]), the likely number of filters required per household at one time (1[5]), and the expected factory yield (∼88%[12]), roughly 3.5 filters are required to deliver 1 FU over 10 years. Rayner[12] reports that retail prices are \$8−35 per filter (average \$16.68), accounting for raw materials, capital investment, maintenance and reinvestment, and marketing. Taking into account the time value of money over 10 years, the full economic cost to deliver 1 FU via the ceramic filter POU technology is approximately \$63.

For the centralized water system, it has been estimated that the initial investment for a system with 40 years of useful life is roughly \$164 per person in South Africa and nearby countries. Operational costs for treatment and distribution of the piped water to individual households account for an additional \$0.20−0.30 per m^3 delivered.[41] Taking into account the time value of money, the full economic cost to deliver 1 FU via the centralized water system is roughly \$221. Thus, the ceramic filter POU technology is less expensive than the benchmark. However, the costs alone fail to capture the full complexity of this comparison, since both systems do not necessarily deliver the same water quality. We therefore defined the cost-effectiveness ratio (CER) of each water treatment system as the cost per FU in each system divided by the quantity of DALYs averted by each system. The results of the cost and cost-effectiveness comparisons between the ceramic filter POU and the centralized system are depicted in Figure 2.

From Figure 2, the ceramic POU technology not only is less expensive per FU than the centralized system but also delivers better cost-effectiveness when accounting for reduction in diarrheal illness. When considering the general population, the filter POU (\$84/DALY averted) is nearly six times more cost-effective than the centralized system (\$466/DALY averted). When considering only children under five, the filter POU (\$47/DALY averted) is three times more cost-effective than the centralized system (\$141/DALY averted). This comparison cannot be performed for the population of adults with HIV, because we were unable to find data for diarrheal reduction among HIV-positive persons using a centralized water treatment system. Still, the ceramic filter exhibits excellent cost-effectiveness (\$1.11/DALY averted) for this especially vulnerable population. For perspective, the World Bank estimates that standard ART treatment typically costs \$6−12 per DALY averted; therefore, the additional cost for the filter should be both manageable and worthwhile as a secondary intervention.[42]

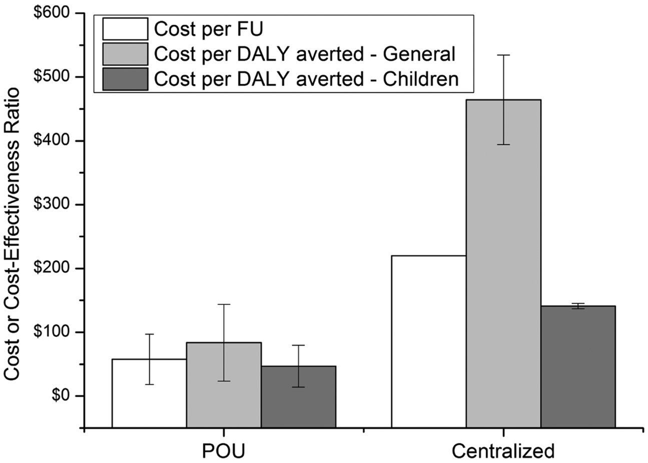

Figure 2. Cost per functional unit (FU) and cost per DALY averted for the general population ("general") and children under five years old ("children"). Data show the comparison between the ceramic filter ("POU") and the benchmark centralized system. White bars represent costs per FU. Gray bars represent cost-effectiveness. Error bars represent empirical standard deviations from Monte Carlo sampling; however, lack of data prevented computation of error bars for the cost per FU in the centralized system. *P*-values for difference between means for the POU vs the centralized system were less than 0.0001 (n = 100,000 trials) for both the "general" and "children" scenarios.

Beyond the comparisons in Figure 2, the ceramic filter POU also exhibits better cost-effectiveness than any of the technologies evaluated by Clasen et al.[43] for the region including South Africa. Their range of reported cost-effectiveness values was $95−180 per DALY averted for the general public. Interestingly, the Clasen[43] study did include evaluation of ceramic filters POU devices; however, their filters were imported from developed countries, and they did not contain any silver to enhance the filter's disinfection capability. These changes resulted in significantly decreased cost-effectiveness compared to what is shown in Figure 2, because more expensive filters were used to deliver poorer-quality treated water. Finally, the WHO's Commission on Macroeconomics and Health (CMH) defines "cost-effective" interventions as those costing less than or equal to three times the gross domestic product (GDP) per capita. Similarly, "very cost-effective" interventions must cost less than one times the GDP per capita.[44] On the basis of these definitions, the ceramic filter constitutes a "very cost-effective" water treatment intervention.[45]

3.3. Environmental Sustainability. The third component of sustainability is environmental sustainability. Although the ceramic filter POU technology has been the subject of several studies regarding its social and economic performances (as noted in Sections 3.1 and 3.2), there has been virtually no assessment of its environmental impacts. Moreover, many published LCA studies have focused on elucidating the environmental impacts of products, processes, or services for industrialized processes in developed countries, whereas fewer have focused on less industrialized countries, almost completely overlooking opportunities for developing world countries to pursue truly *sustainable* development. This study evaluates the environmental sustainability of locally produced ceramic filters, to understand how they perform compared to the centralized water treatment systems which have become the technology of choice in most industrialized nations.

As shown in Figure 1, the environmental LCA of the ceramic filter POU device accounted for extraction of mostly local raw materials, transportation of materials and energy to the factory, manufacturing of the filter, use phase, and end of life. Sections 2.1.1 and 2.1.2 of the SI outline the LCA calculations for procurement and transportation of clay, combustible material, water, silver solution, and energy sources (e.g., wood, diesel, etc.). Section 2.1.3 of the SI summarizes LCA calculations for filter production processes, highlighting the dramatic variability that currently exists among operating filter factories. We

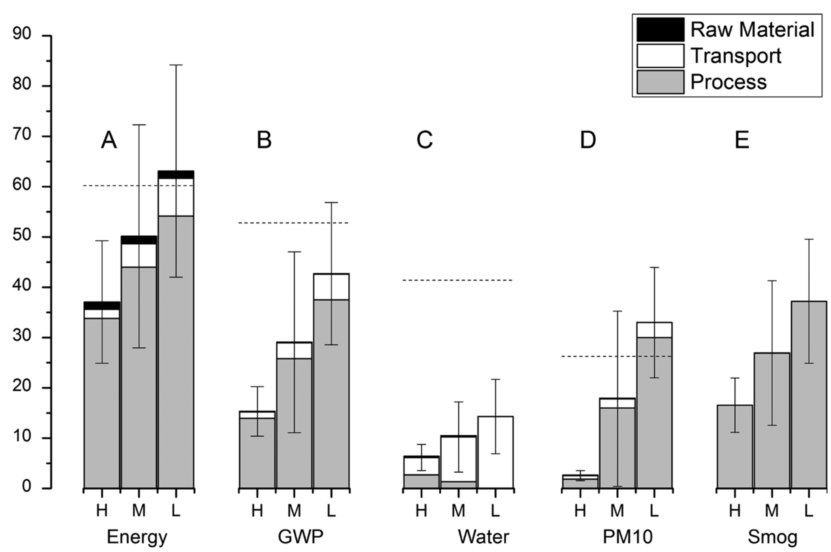

Figure 3. Environmental impacts per FU: (A) Total energy use (×10 MJ), (B) global warming potential (kg CO_2-eq), (C) water use (m^3), (D) particulate matter emissions (PM10) (g), and (E) smog formation potential (g NO_x-eq). Error bar represents one standard deviation from iterative Monte Carlo simulation. Dashed horizontal lines represent corresponding environmental impacts from the benchmark centralized water system. The value of smog formation potential for the centralized system (0.1361 g) is too small to be depicted on these axes in panel E. Column labels "H", "M", and "L" correspond to high-tech, medium-tech, and low-tech scenarios, respectively. *P*-values for the difference between means for "high vs. medium", "medium vs. low", and "high vs. low" were less than 0.0001 (n = 100,000 trials) for all five evaluated LCA impacts.

accounted for this variability using three different scenarios: high-tech, low-tech, and medium-tech. The "high-tech" scenario assumes that all production processes are carried out using electricity or other advanced fuels (i.e., propane). In contrast, the "low-tech" scenario assumes that all production processes are carried out using either manpower or primitive fuels (i.e., wood). The third scenario, "medium-tech" reflects the expectation that most filter factories will use some combination of high-tech and low-tech processes; as such, this scenario is expected to be most representative of the filter factories currently in existence.[38] This scenario was parametrized via random selection of which production steps were completed using either high-tech or low-tech methods. The LCA impacts of all steps were then added together over the entire filter life cycle. Use of Monte Carlo sampling (i.e., 100,000 trials) ensured adequate coverage of all combinations for high-tech and low-tech options for the various steps. It was assumed that the manufacturing (production) stage is the only life cycle stage subject to such wide variability. Finally, Section 2.1.4 of the SI describes LCA modeling of the use phase and end-of-life. Both of these life cycle stages accounted for negligible LCA impacts, and it was assumed that the filters would be used for some other purpose (i.e., storage) once they were no longer suitable for water treatment.

Figure 3 summarizes the environmental performance of the ceramic filter POU technology relative to that of the centralized water system. Five key LCA impacts were evaluated for the production of 1 FU in each system: energy use (panel A), global warming potential (panel B), water use (panel C), particulate matter emissions (PM10) (panel D), and smog formation potential (panel E). In all panels, the life cycle impacts for the high tech, medium tech, and low tech ceramic filter scenarios are plotted using column graphs. For comparison, the corresponding performance for the centralized water system is shown using a dashed line. It should be emphasized that the environmental burdens of the centralized system were scaled to account only for production of the FU (i.e., 37,960 L for *drinking*), even though centralized systems produce much larger volumes of treated water than can be consumed by one household and this water is typically used for other uses in addition to drinking (e.g., bathing). The numerical data corresponding to Figure 3 are also presented in Table S11 of the SI.

There are three important observations arising from Figure 3. These pertain to: (1) the relative performances of the high-tech, medium-tech, and low-tech ceramic filter scenarios; (2) the breakdown of each LCA impact by life cycle stage; (3) and comparison between the ceramic filters and the centralized water system. These items are discussed in the following paragraphs.

First, for all LCA impacts, the performance of the medium-tech scenario is always between that of the high-tech and low-tech scenarios. This offers some validation for the randomization approach used to parametrize the medium-tech scenario. From a recent survey of existing filter factories,[12] many factories use some combination of high-tech and low-tech subprocesses. Thus, the medium-tech scenario likely captures "typical" filter factory performance even though it may not directly correspond to any specific, individual factory configuration. Further comparison of the three scenarios reveals, perhaps unexpectedly, that the high-tech scenario results in lower environmental burdens than the low-tech scenario for all evaluated LCA impacts. This suggests that adoption of appropriate advanced technologies improves the overall environmental performance of ceramic filter production. In particular, the use of propane-fueled kilns instead of wood-fueled kilns significantly improves both energy efficiency and particulate matter emissions (PM10). Thus, it is beneficial that the use of propane kilns appears to be on the rise among existing and new filter factories.[38]

Second, regarding the breakdown of each LCA impact by life cycle stage, the manufacturing stage is by far the largest contributor to all environmental burdens except water use. The subprocesses comprising this life cycle stage include: grinding the clay, mixing the clay with water and combustible material, pressing the clay into a pot-shaped filter, firing the filter to form the ceramic and burn off the combustible material, and coating the filter with a solution of silver nanoparticles. (See Section 2.2 of the SI for more details.) Many of these subprocesses can be achieved using either "high-tech" or "low-tech" procedures; therefore, the relative contribution of each subprocess to the overall impact varies by scenario and by LCA impact category. For the medium-tech scenario, the relative contribution of each subprocess is roughly as follows: firing $\gg$ grinding $\approx$ mixing $\approx$ pressing $\gg$ coating with silver. The transportation life cycle stage is the greatest contributor to overall water use and second largest contributor to all other environmental impacts. Less than 0.1% of each transportation burden accounts for transport of the silver nanoparticles from Europe or China to Africa via airplane and diesel truck. This is somewhat surprising, given that this material must travel 3000−9000 km to arrive at a filter factor; however, the very large distance is evidently offset by the very small quantity of silver required to produce 1 FU (~225 mg). All other materials are locally produced, which gives them very low transportation burdens. Similarly, the use-phase and end-of-life burdens were essentially negligible.

The third and last observation from Figure 3 pertains to the LCA-based comparison between the ceramic filter POU technology and the centralized water system. LCA calculations for the centralized water system were summarized in Section 2.3 of SI. From Figure 3, the ceramic filter offers better environmental performance than the centralized water treatment system in all evaluated impact categories other than smog formation potential. This was an unanticipated result of this study, but breakeven analyses for the medium-tech scenario indicate that this trend holds true so long as the daily volume of water treated per household is greater than 8.6 L. (See Table S10 of SI.) At daily treatment volumes less than this value, the ceramic water filters deliver larger environmental burdens per FU than the centralized water system; however, the WHO recommendation of 2 L of drinking water per day per individual requires that at least 10.4 L be treated daily for a household size of 5.2 persons.[2] Finally, the poor smog performance of the ceramic filter arises almost entirely (99%) from firing the filters. From panel E of Figure 3, use of high-tech equipment and/or procedures (e.g., high efficiency propane kiln) instead of low-tech options (e.g., wood kiln) significantly reduces smog formation potential for the ceramic filter but does not make it less than that of the centralized water system. Thus, stakeholders will need to evaluate to what extent smog formation is a significant priority compared to all other environmental impacts.

To understand the "environmental cost-effectiveness" of the filters compared to the centralized system, it was necessary to normalize the environmental burdens from Figure 3 in a manner analogous to what was done for economic costs in

Section 3.2. Each type of LCA impact was thus divided by the quantity of DALYs that could be averted using either technology. Data corresponding to the ceramic filter's medium-tech scenario were used for these calculations. Results are presented in Figure 4 (and Table S12 of the SI). These data

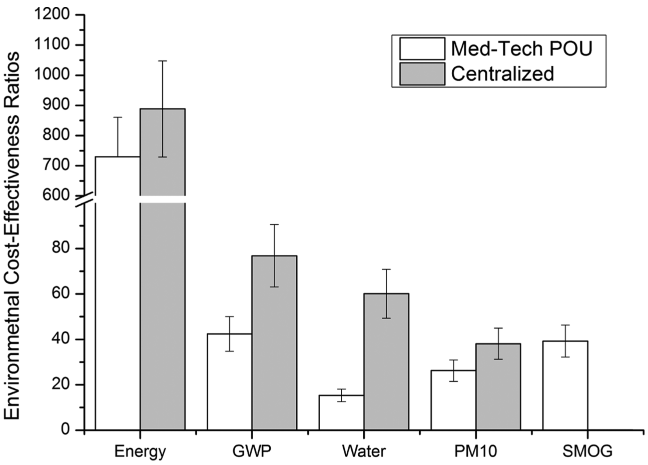

Figure 4. Environmental impacts per FU for the POU ceramic filter technology and the centralized water system, normalized using the quantity of DALYs averted. Evaluated impacts include: energy use ("energy") in MJ, global warming potential (GWP) in kg CO_2-eq, total water consumption ("water") in m^3, particulate matter emissions ("PM10") in g, and smog formation potential ("smog") in g NO_x-eq. All ceramic filter POU data correspond to the medium-tech LCA scenario. DALYs correspond to the general population. Error bars represent empirical standard deviations derived from Monte Carlo sampling. *P*-values for difference between means for "POU vs. centralized" were less than 0.0001 (n = 100,000 trials) for all five evaluated LCA impacts.

closely mirror Figure 3, whereby the ceramic filter offers better environmental cost-effectiveness than the centralized water system for all evaluated impacts except smog. The use of the DALY normalization appears to accentuate the differences between the POU technology and the benchmark, making it seem more preferable (compared to Figure 3) on the basis of energy, water, PM10, and GWP but less preferable on the basis of smog formation potential.

3.4. Implications. This study presents quantitative evidence that silver-impregnated ceramic filters deliver better quality of life improvements, better cost-effectiveness, and enhanced environmental performance compared to centralized water systems of the developing world. This convergence of social, economic, and environmental criteria offers clear indication that the ceramic filter POU technology is a more *sustainable* choice for drinking water treatment in developing countries than the "one-size-fits-all" centralized treatment approach that has been widely adopted in industrialized countries. The sustainability benefits of the ceramic filter POU technology are especially pronounced for vulnerable populations such as children under five and persons with HIV. Thus, this technology is a compelling option for delivery of safe drinking water in developing countries.

ASSOCIATED CONTENT

Supporting Information

Detailed model documentation, cost analysis, and DALY calculations. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: lmcolosi@virginia.edu; tel:1 (434) 924-7961.

Notes

The authors declare no competing financial interest.

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