

Research Paper

Comparative life cycle assessment of four commonly used point-of-use water treatment technologies

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ABSTRACT

Across the globe, billions of people lack access to safe drinking water. Many different point-of-use (POU) technologies have been developed that significantly reduce the disease-causing pathogens found in untreated water. With many different technologies available, it can be difficult to choose which technology to implement in specific areas. Beyond the cost of each technology, the environmental impacts could bring additional harm to a community. Life cycle assessments (LCAs) are used to make comparisons across different technologies. This study uses an LCA to compare boiling water, ceramic water filters, BioSand filters and POU chlorination as treatment options in the rural community of Thohoyandou, Limpopo Province, South Africa utilizing previously published, open-access data. Global warming potential, water use, energy use, smog formation, particulate matter and land use are the studied environmental impacts. Results found that boiling had the most impact on energy use, global warming potential, smog and land use; chlorination had the greatest impact on particulate matter and water use. A cost comparison found boiling water to be most expensive at 0.053 USD per liter and chlorination to be least expensive at 0.0005 USD per liter.

Key words | climate change, life cycle assessment, point-of-use water treatment

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HIGHLIGHTS

- Comparative life cycle assessment of boiling, ceramic water filters, BioSand filters and chlorination.
- Environmental impact assessment of energy use, global warming potential, smog formation, particulate matter, water use and land use.
- Cost analysis of point-of-use water treatment technologies.
- Results found ceramic water filters and chlorination to be the most sustainable technologies of the four compared.

INTRODUCTION

Worldwide, 2.1 billion people do not have access to safe drinking water (UN 2018). Lack of access to safe drinking water can result in a great deal of time being spent walking to water access locations and carrying the water back (Gadgil 1998). Furthermore, drinking untreated water can

result in preventable diseases, leading to an average of 485,000 deaths (World Health Organization 2019a). When people collect their water directly from a source – whether a groundwater well, lake or stream, the water is untreated and may contain pathogens. Additionally, 2 billion people

still lack access to basic sanitation facilities such as toilets or latrines and 673 million still defecate in the open, which can commonly contaminate local drinking water sources (World Health Organization 2019b). Point-of-use (POU) water treatment systems can be beneficial in treating collected water and storing in the home. This method can reduce the risk of recontamination through the use of proper storage (Quick *et al.* 1999). Conversely, installing piped water systems in rural communities can be too expensive and create unreliable water sources as population density increases (Mintz *et al.* 2001).

There are many different options for POU water treatment systems. These systems range in cost, materials required, knowledge to use and treatment effectiveness. Three main categories for treatment options are disinfection products, filtration systems and solar water disinfection (Clasen *et al.* 2015). Examples of filtration systems are ceramic water filters (Bielefeldt *et al.* 2009), BioSand filters (Stauber *et al.* 2006) and LifeStraw filters (Walters 2008). Other common POU technologies include mixed oxidant gas systems (Kerwick *et al.* 2005), pasteurization (Islam *et al.* 2006), UV disinfection (Brownell *et al.* 2008) and ozone treatment (Upadhyayula *et al.* 2009). Clasen *et al.* (2015) conducted a comparison of existing trials for POU water treatment systems. The trials focused on chlorination (30,746 participants), flocculation/disinfection (11,788 participants), filtration (15,582 participants) and solar disinfection (3,460 participants) (Clasen *et al.* 2015). Following the most used technologies, the study presented here will focus on two filter types (ceramic water filters and BioSand filters) and chlorination using sodium hypochlorite. Additionally, boiling water will be included because about half of the world's population (around 3 billion people) rely on biomass burned in the home for water treatment (Bruce *et al.* 2002). The goal of this study is to compare the environmental impacts of each technology. Previous studies have made direct comparisons of the social implications of each, but to our knowledge there has not been a direct comparison of the environmental impacts of these four technologies.

Although POU technologies have been widely tested, studied and implemented, the continued use of technologies remains low in the developing world. One study found that although families experienced a 39% reduction in days with

diarrhea, only 5% of families within a study community were considered active repeat users of coagulant–flocculant when left to continue regular water treatment on their own after intervention (Luby *et al.* 2008). Families were provided with the water treatment during the study, but after the study were required to purchase their own. Surveys of the community found that some said the cost was too high (Luby *et al.* 2008). Other studies found that although families would use a treatment technology during a study where consistent encouragement was provided, once the study ended families would begin to revert to past habits (Quick *et al.* 1999). In the case of flocculant–disinfectant, after low sales persisted in the study area of rural Guatemala, the manufacturing company discontinued their marketing in that area (Luby *et al.* 2008). Another study found that product unavailability, cost of product and unwillingness to pay market price were barriers that prevent acceptance of POU technologies that consistently rely on the supply chain (Sobsey *et al.* 2008). A study conducted in South Africa found that 68.3% of households have a total income less than 10,000 Rand (550 USD) per month (Oni *et al.* 2010). Introducing a water treatment technology that has a high startup or maintenance cost could put an extra burden on families already struggling. It is therefore imperative to assess the economic costs of different water treatment technologies when considering their ultimate sustainability. Another goal of this study can be used to compare both the environmental impacts and the cost of these four technologies. Then, implementation can be focused on one technology to improve the number of families who continue to use the technology on their own. This study is intended to provide insight on which technology would have fewest environmental and financial impacts on a community prior to introducing the technology to a new area.

The goal of this study is to evaluate the sustainability of different POU water treatment options in developing countries using only secondary data from open-access sources. We will do this by (1) comparing the environmental impacts of several highly used POU water treatment technologies and (2) comparing the costs of different POU technologies. Our baseline technology will be boiling water – it is a widely used and an effective form of treatment but can lead to deforestation, increased air pollution, increased carbon dioxide emissions and is detrimental to

human health (Clasen *et al.* 2008). Typically, fires for cooking or boiling water in the home are either open fires or in poorly functioning stoves, which can lead to many health effects from poor indoor air quality (Bruce *et al.* 2002). Shifting away from boiling water to other water treatment technologies could reduce the amount of time a fire is burning in the home, but the question remains whether these other technologies could truly reduce the environmental impacts. A life cycle assessment (LCA) can answer the question of whether other technologies can be an improvement over boiling water. To our knowledge, this is the first study to directly compare four different technologies that are commonly used. Previous work by Ren *et al.* (2013) compared ceramic water filters to a centralized treatment facility, but those are two very different treatment options. Our study is specifically focused on POU water treatment. We will assess boiling, chlorination, ceramic water filters and Bio-Sand filters.

METHODS

LCAs can be broken into four steps: (1) goal and scope definition; (2) life cycle inventory (LCI) analysis; (3) life cycle impact assessment and (4) interpretation and improvement analysis (Brent 2003).

System boundaries

This LCA is intended to focus on developing world impacts. For the purposes of this study, we chose Limpopo Province in South Africa. However, the data were entirely collected from EcoInvent (Wernet *et al.* 2016) and no work was conducted within South Africa. In rural, developing areas such as Limpopo Province, people are highly vulnerable to environmental degradation because they have limited environmental controls. Specifically, communal farming is predominately practiced and highly prone to climatic conditions (Mmbengwa 2015). Burning wood releases nitrogen oxides, which react with sunlight to form photochemical smog. Nitrogen oxides can pose a health risk because they are damaging to the respiratory system (Munalula & Meincken 2009). Carbon dioxide, methane and dinitrogen monoxide are all contributors to global warming by

absorbing infrared radiation instead of releasing that heat from the environment. Methane and nitrous oxides have been found to absorb infrared radiation much more strongly than carbon dioxide (Lashof & Ahuja 1990). The absorbed infrared radiation leads to increased temperatures (Abdel-Khalik 2000), which is expected to lead to changes in precipitation. Extreme storms are expected to carry more rainfall leading to increased floods and rainfall in midlatitudes is expected to become even more scarce (Speth 1998). These global warming enhanced weather changes are predicted to cause a 10–30% decrease in agricultural production in Africa and Latin America (Watson 2000).

Carbon dioxide emissions have risen 35–40% since the middle of the 19th century (Bradley 2000). Developed nations underwent industrialization with no restrictions or policies against greenhouse gas emissions. Developing nations are now beginning to industrialize but have new restrictions on greenhouse gas emissions that were not in place for previous countries (UN 1972). These restrictions are intended to prevent the extreme increase in greenhouse gas emissions that developed countries experienced. To address these smaller-scale conditions for developing countries to see how implementation of new technologies impacts the environment, this LCA is focused on a local assessment rather than a global assessment. As such, this study will be conducted as if a factory for each technology exists in the town of Thohoyandou, located in the Limpopo Province of South Africa. It will be assumed that filters are distributed from Thohoyandou to the entire province of Limpopo. Products made outside of South Africa will be excluded. This study takes a more local approach versus global approach because the impacts from these technologies will be comparatively greater at the local scale versus the global scale given their small environmental impacts when compared with many other products used in developed countries. Such LCAs can help to inform policy decisions (Tukker 2000) in areas such as aquaculture (Ford *et al.* 2012) and biomass sources (Godard *et al.* 2013). Moreover, Ford *et al.* (2012) highlights that environmental impact assessments may have more meaning at the local scale as they measure direct impacts on ecosystems. This LCA is intended to provide insight for community developers on which POU water treatment technologies will have the least impact on their local environment.

Goal and scope definition

The goal of this LCA is to conduct a comparative analysis across four different POU water technologies and compare their impacts in terms of energy use, global warming potential, particulate matter, water use, smog production and land use. Energy use represents the dependence on electricity, which primarily relies on fossil fuels. In South Africa, coal is a primary energy source and can have significant impacts on the local environment and human health (Friedrich *et al.* 2009; Munawer 2018). In the case of boiling water, energy usage represents burning fuelwood, which can also lead to environmental and human health impacts (Munalula & Meincken 2009). Global warming potential is calculated based on the emission of three greenhouse gases: carbon dioxide, carbon monoxide and dinitrogen monoxide. Global warming potential is an important factor because of how vulnerable developing nations are to climate change (Churchill & Saunders 1991). Particulate matter and smog formation represent impacts on air quality. Increases in both categories could lead to reduced air quality and impacts on the population's health (Peters 2005; Rani *et al.* 2011). Water use was chosen for two reasons. First, the use of water in industrial processes could lead to reduced water quality from the release of poorly treated greywater. Dungeni *et al.* (2010) found three out of four wastewater treatment plants in the Gauteng Province of South Africa to have *Escherichia coli*, *Salmonella typhimurium* and *Vibrio cholerae* present in the treated effluent (Dungeni *et al.* 2010). Secondly, reliance on technologies with high water usage could become problematic as water scarcity increases (Vairavamoorthy *et al.* 2007). Although South Africa is listed as water stressed and not water scarce, 11 out of 19 water management areas are in water deficit (Otieno & Ochieng 2004). Land use represents the amount of land that would be required for specific materials. Reliance on a technology with a high land use could result in overuse of resources, especially given the high rate of population growth in sub-Saharan Africa.

A regional-focused comparison based on the town of Thohoyandou in the Limpopo Province of South Africa was conducted. Data were solely obtained from EcoInvent to model each technology. This LCA was conducted using secondary data from EcoInvent because no physical work was conducted in South Africa nor were primary data collected directly from factories and processes used in the

analysis. It is acceptable in LCA to use secondary data (Hawkins *et al.* 2013; Howe *et al.* 2013; Vahidi & Zhao 2017). When necessary, factories and source locations were chosen from local businesses in South Africa. The distance from Thohoyandou and the products they carried were the primary factors when choosing which suppliers to use. When possible, datasets in EcoInvent pertaining to South Africa were used. Otherwise, the global approximations were used.

Functional unit

In a comparative LCA, the functional unit is an important factor in making fair comparisons across all technologies. The amount of water used per day per person varies greatly from one location to another. The range of drinking water per day is from 2 to 5 liters per person as a true minimum to support life in a temperate climate (Gleick 1996). To be consistent with previous studies (Ren *et al.* 2013), 2 liters per person per day were used. The 12-year lifespan of the BioSand filter was used as the duration of the study because it is the technology with the longest lifespan (Sisson *et al.* 2013). Using an average household size of 5.3 in sub-Saharan Africa (Bongaarts 2001), the functional unit is defined as 46,428 liters. Therefore, the quantities of each technology needed to treat 46,428 liters of water in the assessment will be considered.

Technology effectiveness

All four of the water treatment technologies are used in practice today. Each has been shown to effectively treat drinking water (Stauber *et al.* 2006; Garrett *et al.* 2008; Bielefeldt *et al.* 2009; World Health Organization 2011) and can be a stand-alone treatment. This study focuses on the environmental impacts of each technology and not the effectiveness of the technologies themselves. Therefore, it is assumed that the effectiveness of each technology is equal and there will be no comparison or normalization of treatment effectiveness.

Water treatment technologies, LCI and impact assessment

The following section discusses each of the four technologies. Additional information can be found in the Supplementary Materials.

Boiling

Boiling water is one of the most universal forms of water treatment. Figure 2 in Supplementary Materials outlines the system boundaries and processes for boiling water. Sobsey *et al.* (2002) found that 1 kg of wood is needed to boil 1 liter of water. In order to treat the functional unit of 46,428 liters of water, 46,428 kg of wood is needed.

Ceramic water filters (CWF)

Ceramic water filters can be produced locally in regions worldwide. The lifespan of ceramic water filters varies based on several different factors, such as breakage or reduced filtration. However, two years is typically used as the average (Rayner 2009). Factories are designed to operate using as many local materials as possible, leading to some factories using different input materials than others. To account for that, this LCA uses information from Lantagne's Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter Report 1 and 2 (Lantagne 2001a, 2001b). Ceramic water filters require colloidal silver to be painted on the outside. However, the amount of colloidal silver required is very minor compared with the other materials such as clay, water and sawdust. More importantly, Laboratories Argenol is the primary provider of colloidal silver and is located in Spain. Because the production process will fully take place outside South Africa, manufacturing of colloidal silver is excluded from this study. The ceramic filters are fired in kilns. The kiln is considered part of the factory, but the wood fuel for firing the kiln is included in calculations. Six ceramic filters will be needed for the 12-year study.

BioSand filters

BioSand filters are an easy-to-use technology that utilizes sand and gravity to treat water. Filters are made from a concrete shell, filled with different coarse sands and gravity filters the water through the system. Materials needed for the BioSand filters include a metal mold, a metal diffuser plate, Portland cement, river sand, gravel, water, and a PVC pipe. Sand and gravel are locally available materials that will need to be transported from their extraction site to the hypothetical factory in Thohoyandou. This study

duration is based on the lifespan of the BioSand filter, so only one filter will be needed to treat the functional unit of water.

Chlorination

Chlorination is often one of the last steps in a water treatment facility, but it can also be used as a stand-alone POU water treatment. Sodium hypochlorite is one of the most commonly used chemicals for treatment and can be made in developing countries (Arnold & Colford 2007). The dosing of sodium hypochlorite to water depends on both the concentration of the solution and the cap volume of available containers. The goal is to use readily available containers. The standard packaging of Population Services International uses a 150 mL bottle with a 3 mL cap (Lantagne *et al.* 2011) and packaging for Waterguard and Sur'Eau are 250 mL bottles. Additionally, the WHO recommends a chlorine residual of 0.2–0.5 mg/L 30 min after treatment (World Health Organization 2004), which may require alteration to the concentration or dosage for specific locations (Lantagne 2008). Each 250 mL bottle of sodium hypochlorite can treat 1,000 liters of water. Therefore, each household will need 47 bottles for the 12-year span.

ECONOMIC COST

Boiling water is widely used and close to 'free' to the consumer because boiling a pot of water prior to, or while cooking does not increase cost substantially. Although the fuel for a fire would be used anyway, a great deal of time is spent collecting the firewood and cannot be spent on something else. One study at two sites in sub-Saharan Africa found that women and girls in Lake Malawi spent a daily average of 63 min collecting firewood, and in Simanjoro Maasai women spent 10 min collecting firewood while girls spent 30 min (Biran *et al.* 2004). A study conducted by Makhado *et al.* (2009) found that villagers sell fuelwood at market for 10R (0.53 USD) per 10 kg. Using the conversion of 1 kg per 1-liter water, there would be a 1R (0.053 USD) per liter cost and 2,451 USD in total for the 12 years. However, fuelwood is also collected by hand from trees and not purchased from the market. This study used calculations

based on all the required fuelwood being purchased from market.

Chlorination, ceramic filters and BioSand filters are often partially covered by NGOs. A bottle of sodium hypochlorite can treat 1,000 liters of water and costs 0.50 USD (CDC 2013). The cost of sodium hypochlorite would be 0.00052 USD per liter. The cost of ceramic filters range from 7.50 to 35 USD, with an average of 15.71 USD (Potters for Peace 2011). The prices can vary based on the factory the filter was made and the material of the receptacle. Some receptacles are plastic, which results in a cheaper filter, others are ceramic, and some are decorated. The unit price of CWF would range from 0.00096 USD to 0.0045 USD per liter, depending on the style purchased. BioSand filters produced and installed by The Water Project cost 70 USD, resulting in a 0.0015 USD per liter cost.

RESULTS

The data for each individual process were obtained from EcoInvent (Wernet *et al.* 2016), and the total contributions to energy use, global warming potential, particulate matter, water use, smog and land use were calculated. Global warming potential was calculated from the emissions of carbon dioxide, methane and dinitrogen monoxide, in terms of carbon dioxide equivalents. This calculation for carbon dioxide equivalents applied a factor of 1 to carbon dioxide emissions, 28 to methane and 265 to dinitrogen monoxide

(IPCC 2014). Particulate matter is the sum of particulate matter with diameters less than 10 μm . Table 1 shows the results of each category and Figure 1 visualizes the impact of each technology, one panel for each of the six categories. Boiling water has the greatest impact on smog, land use, global warming potential and energy use. Chlorination has the most impact on particulate matter and water use.

In terms of the cost comparison, LCAs do not always take the direct cost of each technology into consideration. This study looked at the environmental comparisons of each technology, but cost is one of the most limiting factors in the study area. Rows 8–12 of Table 1 include the cost of one unit of treatment technology, the cost for 12 years of treatment and a unit cost of water treated.

DISCUSSION

Boiling water had the most impact on four of the six categories: energy use, global warming potential, smog formation and land use. Chlorine had the most impact on particulate matter and water use, but had the least impact on energy use, smog and land use. The low impact in three of the categories was enough to offset the high impact of two categories and make it one of the better options. Ceramic water filters had the least impact on global warming potential and ranked second in three other categories. Consistent low impacts across categories is what drove the overall impact of ceramic filters to tie with

Table 1 | Results of the life cycle impact assessment using data from EcoInvent

Indicator	Boiling	BioSand	CWF	Chlorination
Energy usage (MJ)	1,025,820	10	533	5
GWP (kg CO ₂ eq)	11,776	1,691	101	181
PM ₁₀ (g)	554	11	152	744
Smog (g NO _x eq)	13,202	47	39	14
Water use (m ³)	1	7	16	72
Land use (m ² *year)	3,092	5	2	0
Unit	10 kg wood	1 filter	1 filter	1,250 mL bottle
Unit cost (USD)	0.53	70	7.5–35 (mean 15.71)	0.50
Total cost for 12 years (USD)	2,451	70	45–210 (mean 94)	23.50
Cost per liter of water (USD)	0.053	0.0015	0.00096–0.0045	0.00052

The impact values for each technology are shown across a range of indicators, measured in unit equivalents. Rows 8–12 cover the economic cost comparison.

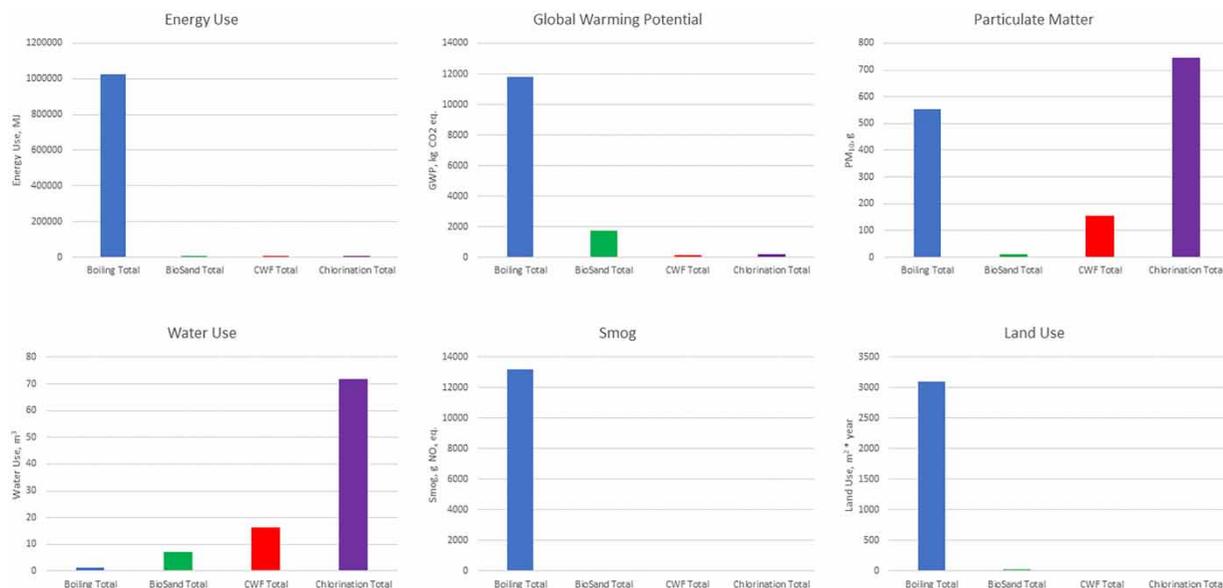


Figure 1 | Life cycle impact assessment (LCIA) results for six different impact categories, measured in unit equivalents. Boiling water had the most impact on global warming potential, smog formation, land use and energy use. Chlorination had the most impact on particulate matter and water use.

chlorination as one of the better treatment options. BioSand filters contributed least to particulate matter. Since water is boiled on fires directly in the home with few precautions made to prevent any potential health concerns from smoke inhalation, and the health impact of boiling is even greater than the other technologies. The one-time production of ceramic water filters, BioSand filters and sodium hypochlorite have less impact on the magnitude of greenhouse gas emissions when compared with the daily burning of wood to boil water.

Boiling water had the highest energy usage. The driving factor was the energy required from the wood to heat the water. Munalula & Meincken (2009) found the average calorific value of the most common wood in South Africa to be 18.86 MJ/kg. The daily reliance on fires to treat water requires a lot of fuelwood. Ceramic water filters ranked second for energy usage, driven by the production of the plastic receptacle. Using different storage containers could alter this finding. BioSand filters ranked third and chlorination had the lowest impact on energy usage. Most of the energy usage for BioSand came from the Portland Cement and PVC pipe production. Chlorination values were driven by the production of sodium hypochlorite.

Boiling water had the highest global warming potential. Burning wood releases gases such as carbon dioxide and

methane, which both contribute to ozone depletion and greenhouse gases (Smith *et al.* 1993). Again, the daily reliance on boiling water significantly increases the impacts to global warming potential. BioSand filters had the second highest impact on global warming potential. The dinitrogen monoxide in the production of Portland cement was the driving factor in the high global warming potential because it is a potent greenhouse gas. Carbon dioxide is the contributor to GWP from boiling and the accumulation of daily boiling over 12 years still exceeds the one-time production of a BioSand filter.

Chlorination releases the highest levels of particulate matter, which was driven by the production of sodium hypochlorite. The production of the plastic bottles had little impact. Boiling water had the second most impact for particulate matter.

Boiling water has the highest levels of smog. Since water is boiled on fires directly in the home with few precautions made to prevent any potential health concerns from smoke inhalation, their health impact is even greater than the other technologies. BioSand filters were the second highest contributor to smog, which was driven by the transport of the filters. The transportation was high compared with other technologies because there were several materials that would need to be produced in factories and then transported

to the hypothetical BioSand filter factory in Limpopo. BioSand filters are the heaviest technology and can weigh up to 350 pounds (160 kg). The concrete filter body itself weighs 150 pounds (70 kg) (Ohorizons 2017). Each filter is comprised of a cement shell and filled with sand and gravel. The additional weight of these materials exceeds the weight of the ceramic filters and chlorination, at 90- and 13-kg total, respectively.

Water usage was highest for chlorination, which was driven by the production of sodium hypochlorite. Ceramic water filters had the second highest impact, followed by the BioSand filters. Boiling water had the least impact on water use. Because most fuelwood is collected from natural forests, the water required to grow the trees was not included. Fuelwood from a plantation could have larger impacts in this category. Similarly, boiling water has the highest impact on land use because of the reliance on trees. Land use is 'the total arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions)' (Mattila *et al.* 2011). Although ceramic water filters also rely on wood for firing the filters, the firing process only occurs once, and the kiln can hold up to 125 filters per firing. Therefore, the impact from burning wood for the filters is much less than boiling water daily. BioSand filters were second highest, although much below boiling, and were driven by the sand and gravel. Chlorination had the lowest impact on land use.

For the 12-year functional unit, 6 ceramic filters, 47 bottles of sodium hypochlorite and 46,428 kg of fuelwood would be needed. Combining the impacts for each category, the overall results show the least impacts for ceramic filters and chlorination, followed by BioSand filters and then boiling. The functional unit was determined by the 12-year lifespan of BioSand filters, which made this the only technology where one unit was required. It is interesting to note that the order of overall environmental impacts is not affected by the lifespan of the technology. Although only one BioSand filter will be needed, it still ranked third as the most environmentally sustainable technology. CWFs are one of the more sustainable technologies because they rely on local, readily available materials. The lack of materials required from industry and transportation to move those materials significantly reduced the impacts of the CWF.

A previous study conducted by Ren *et al.* (2013) compared the social, environmental and cost-effectiveness of ceramic water filters and centralized water treatment. For the LCA, Ren *et al.* compared five impact categories: energy use, water use, global warming potential, particulate matter emissions and smog formation potential. The ceramic water filters showed better performance than the centralized water treatment in all categories except for smog formation potential, which was most likely higher for CWF because of burning wood to fire the filters (Ren *et al.* 2013). Our results agreed that the ceramic filters are one of the more environmentally sustainable technologies. Furthermore, our study focused specifically on POU water treatment systems.

Embodied energy is a similar concept to LCA, but compares the energy consumed by all processes in the production of a specific good. A study conducted in West Africa compared the embodied energy of eight different water treatment options: four were POU technologies and four were source-level technologies (Held *et al.* 2013). Results showed that boiling water was more than two orders of magnitude larger embodied energy than all other technologies. Ceramic filters also had a higher embodied energy because of the energy required to fire the filters. BioSand filters and household chlorination had a lower embodied energy. Although the embodied energy of producing the filters was so high, the low reliance on human energy to operate the filter made a fair tradeoff between the two forms of energy, making the ceramic filters an ideal technology (Held *et al.* 2013). Our results confirm energy use of boiling water much higher than any other technology. Compared with the other three technologies, we found that ceramic filters have the least impact on the environment. We did not consider the amount of energy exerted by the user in the water treatment process.

A study conducted by Sobsey *et al.* (2008) compared five technologies for their ability to treat quantity of water, water of different qualities, ease of use, cost and dependence on the supply chain. BioSand filters received the overall highest score, followed by ceramic filters, free chlorine disinfection, solar disinfection and combined coagulant-chlorine systems. The reliance on the supply chain and lack of ability to treat water of varying qualities drove the lower score for chlorine (Sobsey *et al.* 2008). Our ranking of environmental

impacts for each technology varied from Sobsey *et al.*'s. The ability of BioSand filters to treat large quantities of water, water with varying quality levels and the lack of reliance on the supply chain made BioSand filters the best option. We did not compare those factors, but based on environmental impacts alone, BioSand filters ranked third, only above boiling water. Chlorination was the worst performer for the Sobsey *et al.* study, but environmentally one of the top two technologies in our study. Field studies conducted in rural Guatemala (Luby *et al.* 2008) confirmed that reliance on the supply chain can be a negative factor on the adoption of water treatment technologies. An ideal study would incorporate both the social and environmental factors. Between the different studies, the order of 'best' technology tends to shift based on what the goals of the study were. In energy-related calculations, boiling water and ceramic filters tend to rank as a non-sustainable technology because of the reliance on burning fuelwood (Held *et al.* 2013). Chlorination, although easy to use, has a high dependence on the supply chain and can be limited in its effectiveness for water of varying qualities (Sobsey *et al.* 2008). Our study differed from Sobsey's because of the impacts studied. Sobsey was more focused on social impacts, whereas this study was focused on the environmental impacts. Those differences in factors are the driving reasons for the different results in the ranking of each technology.

Looking at per unit price, sodium hypochlorite is lowest, then BioSand filters, ceramic water filters and boiling water are the most expensive. However, BioSand filters and CWF have high up-front costs for users. Several studies have investigated the importance of having households purchase their own water treatment technology rather than receive it for free (Lantagne 2001a; Luby *et al.* 2008). The concept is that if families invest the money in the filter, they are more likely to use and maintain it. Additionally, the CWF and BioSand filters require no additional cost throughout their lifetime. Once the purchase is made, the user can continue to receive treated water for 2 years (CWF) or 12 years (BioSand) with some regular maintenance.

Beyond the four water treatment technologies presented here, there are many other options available. Solar disinfection (SODIS; Amienyo *et al.* 2013), LifeStraw (Walters 2008) and silver-impregnated antimicrobial papers, called Folia

Filters (Dankovich & Gray 2011) are among other examples. SODIS is a treatment example that could potentially have very few impacts on the environment. SODIS requires filling a clear plastic bottle with untreated water and leaving it in the sun for at least 6 h (McGuigan *et al.* 2012; Amienyo *et al.* 2013). Plastic bottles are often purchased as packaging for other items and then discarded. If SODIS were used, the bottles could be refilled and used for treatment prior to discarding the bottle. No additional energy or materials would be added, only the lifespan of the bottle would be extended. Other treatments such as the Folia Filters and LifeStraw would be manufactured in a factory. Therefore, these additional technologies, similar to the BioSand filters, may have many materials and processes.

One of the limitations of this study is the quality of the data. The data used here were limited to open-access and free data sources, which caused some limitations on the accuracy. For example, some of the datasets were based on global averages and not specific to South Africa. Using secondary data like this is allowable in LCAs when primary data are not available (Klopper & Grahl 2014). Now that the basic flows have been understood, exchanging the existing model steps could improve the accuracy of the LCA as more site-specific data become available. Future studies could improve by using data more relevant to the study area and include more technologies.

CONCLUSION

LCAs can provide useful insight to compare the impacts of choices to find a truly sustainable option. This study presented a comparison of four water treatment technologies for POU water treatment in rural South Africa based on secondary data and found that boiling water had the greatest impact on smog, land use and global warming potential. Ceramic water filters had the greatest impact on energy use, while chlorination had the greatest impact on particulate matter and water use. As for cost, boiling water has the lowest up-front cost to the consumer but the highest total cost and cost per unit of water treated. This study used the assumption that all firewood is purchased from market. Although this may be true for cities, rural communities often collect firewood by hand and do not pay. BioSand filters have a long

lifetime, which make the per liter of water treated cost low, but the up-front cost of 70 USD per filter could prevent access for some families. From the six impact categories studied here, ceramic water filters and chlorination are the most sustainable options. The long lifespan of BioSand filters reduces the accumulated impacts from repeated purchases of the technology. For ceramic filters, the reliance on simple, local materials reduces impacts from industry and transportation. An LCA could be beneficial in determining which technology to target when outside resources aid in improving drinking water technologies in developing areas. Installing the same systems as developed areas, such as centralized water treatment and distribution, may not be feasible for many developing areas. This study is intended to aid community decision-makers when selecting new technologies to implement in rural locations. Choosing truly sustainable options for the community to reduce impacts on the environment could prevent future environmental implications.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 23 July 2020; accepted in revised form 9 October 2020. Available online 27 October 2020