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Sustainability of novel water treatment technologies in developing countries: Lessons learned from research trials on a pilot continuous flow solar water disinfection system in rural Kenya

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A B S T R A C T

The transition from laboratory research to pilot scale trials can be challenging for novel water treatment technologies. This transition is even more complex for technologies intended for use in a developing country context due to cultural, infrastructural, financial and capacity related challenges. This research looks at the lessons learned from a pilot installation of a continuous CPC solar water disinfection system in a rural community of Kenya. This project was implemented with local and international partners, however the monitoring and evaluation phase collapsed due to the breakdown of these partnerships. A visit to the project site three years after installation revealed significant problems with the system due to drought and flash flooding. A second project phase was funded through crowdfunding in order to rehabilitate the damaged system and provide an alternative water source for the community during periods of drought. Post project evaluation of both project phases showed that the engagement of local implementing partners is essential for ensuring community participation and effective monitoring and evaluation, as the priorities and presence of international implementing partners can easily change in the medium to long term. More external assistance is required for pilot projects using novel technologies than for those using well-established water treatment systems, particularly in terms of operation and maintenance challenges which may arise in the short to medium term. This requirement for external support significantly impacts the sustainability of these interventions. The performance of the continuous flow system while it was in use was found to be satisfactory and feedback from the community regarding operation of the system and quality of water was positive. Both project phases revealed the need for some small design changes, such as inclusion of air-bleed valves, which would significantly improve system operation for future pilot projects. The project experience also illustrated the need for better understanding of the behaviour of both surface and groundwater, given increasingly unpredictable weather patterns as a result of climate change.

1. Introduction

The transition from laboratory scale research to full scale trials for new water treatment technologies can be challenging. This transition can be complicated further if the technology is intended for use and requires trials in a developing country context, where issues such as cultural preferences, poor infrastructure, financial constraints and insufficient capacity are often present. The history of water treatment projects in developing countries over the past number of decades has shown significant problems with regard to sustainability (Nauges and Whittington, 2010; Esposto, 2009; McConville and Mihelcic, 2007), even when well-established systems are employed, and this paper aims to put some focus on the particular challenges faced when attempting to trial a new water treatment technology for use in developing countries.

Water treatment methods are often categorised as either household water treatment (HWT) or community water treatment systems. HWT (also called point of use treatment) has been promoted extensively over recent years as the most appropriate way to deal with the issue of contaminated drinking water in developing countries, particularly in rural environments. It can be a good option for relatively small quantities of water transported by hand from a contaminated source and when community resources are insufficient for a central system (UNICEF et al., 2012). The extent of reported household water treatment in low and middle income countries is high, with 33% of households or 1.1 billion people treating their drinking water at home (Rosa and Clasen, 2010). One limitation of HWT is that it does not address issues of water supply,

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which is frequently the main problem faced by communities, particularly in arid regions. Community based water treatment methods often address supply issues more comprehensively than HWT. Such decentralised systems can be appropriate when a water source, even though it may be somewhat contaminated, is able to serve a larger population than can be served by household level or individual treatment systems and where community resources are adequate to cover the cost of construction, operation and maintenance of a simple community-level treatment system (UNICEF et al., 2012).

The particular water treatment method being trialled in this case study is a continuous flow solar disinfection system, aimed at providing a community water treatment solution for a rural village in Kenya. The use of sunlight for water disinfection is now well established and given that approximately 663 million people in the world still lack access to safe drinking water and over 2.4 billion to adequate sanitation (UNICEF and WHO, 2015), technology based upon this process could provide a low cost, low maintenance solution for village scale water treatment. The UV fraction, red and infrared radiation from solar light inactivate pathogens using three distinct mechanisms: absorption of UV disrupts organism DNA, photochemical reactions create highly reactive species which damage/oxidise cellular components and temperature related effects due to the absorption of red and infrared light by water (Davies et al., 2009). A variety of solar disinfection systems have been tested over the past number of decades and these can largely be grouped into batch and continuous flow solar systems.

SODIS (solar water disinfection) is the most common and simplest approach to solar disinfection. It is a batch method of treating water and consists of filling clear polyethylene terephthalate (PET) bottles or clear plastic bags (e.g. Gutiérrez-Alfaro et al., 2017) with water and exposing them to direct sunlight for 6 h, after which pathogens are inactivated or destroyed. Preliminary treatment such as filtration is recommended if turbidity is greater than 30 NTU. The system has been shown to be effective against a wide range of bacteria and viruses (McGuigan et al., 2012; Meierhofer et al., 2002). The concept is simple and so it is ideal for individuals, households, small communities and refugee camps. The SODIS method is currently used by an estimated 4.5 million regular users worldwide, predominately in Africa, Latin America, and Asia, and is recognised and promoted by the WHO, UNICEF, and the Red Cross as an effective household water treatment method for developing countries (EAWAG, 2014; McGuigan et al., 2012; Byrne et al., 2011).

Specific drawbacks to the basic SODIS system include that the capacity of the bottles (or bags) is limited to a maximum of 3 L of water at a time and two days of consecutive exposure are needed under skies with more than 50% cloud. In addition, the user has no means of knowing when water has been treated sufficiently (Polo-López et al., 2011). SODIS reactor bottles are also only illuminated on the upper side, so a large fraction of the available radiation cannot actually reach the water. Efforts have been made to address the drawbacks of the basic SODIS system, with considerable success. For example, using various low cost reflectors and enhancing absorption by painting areas of the bottles black (Martín-Domínguez et al., 2005); use of mirrors and foil behind bottles (Hindiyeh and Ali, 2010) and use of SODIS bags as an alternative to PET bottles is also being tested as a way of maximising the illuminated area and penetration of UV (Gutiérrez-Alfaro et al., 2017; Lawrie et al., 2015; Saladin, 2010).

There is a large body of research on SODIS and other HWT methods and their impacts. This includes SODIS trials in Cambodia, Kenya and South Africa which found significant reduction in the frequency of diarrhoeal episodes among trial groups of children under 5 (Du Preez et al., 2011; McGuigan et al., 2011; Du Preez et al., 2010; Conroy et al., 2001). Despite this growing body of research, a review of HWT (filtration, chlorination, chlorination with flocculation, and SODIS) in terms of acceptability, scalability, adverse effects, and non-health benefits by Schmidt and Cairncross (2009) showed inconclusive results. Hunter (2009) also found that while sufficient evidence existed as to the efficacy of, for example ceramic filters, it is imperative that proper trials of all HWT disinfection methods be carried out, including SODIS, before further projects are implemented, as the effectiveness of these systems is not clear in terms of improvement in public health in the long term.

Although the majority of solar disinfection research has been on batch systems, some continuous flow solar disinfection systems, which have the potential to act as larger scale community systems, have been designed, including the system examined in this paper. Acra et al. (1990) tested two separate solar reactors in the late 1980s, which proved effective against *Streptococcus faecalis, coliforms* (present in the fresh clarified sewage obtained from the city sewer) and cultured *E. coli*. Vidal and Diaz (2000) performed experiments at both the pilot scale and the laboratory scale on a low-cost compound parabolic concentrator (CPC) reactor with results showing the inactivation of *E. coli* and *Enterococcus faecalis*. Equally, McLoughlin et al. (2004a,b) and Rincón and Pulgarin (2004) carried out tests to investigate *E. coli* inactivation on small-scale continuous flow reactors using different shaped solar collectors. Ubomba-Jaswa et al. (2009) examined recirculating photoreactor systems with volumes of 14 and 70 L. Water was exposed to sunlight for 5 h but findings revealed that the interrupted nature of the UV dose, due to the recirculating nature of the system, had a negative effect on disinfection. Polo-López et al. (2011) developed a single-pass sequential batch photoreactor. The enhanced CPC photoreactor automatically dispensed treated water into a collection tank, once a pre-determined UV dose had been received. Fabbricino and D'Antonio (2012) studied thermal effects on a pilot scale continuous plug flow reactor capable of serving about six people. Temperature was found to play an important role in the disinfection process, even in cases of limited solar radiation intensities, and a solar concentrator facilitated better performance. A comparison between transparent and black-painted glass reactors showed no difference. Kalt et al. (2014) developed a rudimentary continuous modular CPC system, using 50 mm diameter borosilicate glass tubes and improvised materials for construction of the CPC. With three modules running in series, they successfully treated 34 L of water in 4 h producing a 4-log reduction in *E. coli* with a residence time of less than 30 min. This was based on an average solar-based UV-A flux ranging from 24 to 36 W/m^2.

Other solar energy-based water treatment systems include solar distillation (Bounds, 2012; Muslih et al., 2010; Koning and Thiesen, 2005), which is important where salinity of the water sources is an issue, and pasteurisation (Onyango et al., 2009; Safapour and Metcalf, 1999; Burch and Thomas, 1998), where solar energy is used to reach water temperatures in excess of 65 °C.

The advantages of continuous systems include increased volumes treated, maximised use of solar radiation during daylight hours and centralised community treatment. In the context of community water systems, Kolb deWilde et al. (2008) carried out an evaluation of an underperforming community-based safe water programme in rural Mexico, which revealed that the water systems were not underused because they had become dysfunctional, but rather, they had become dysfunctional because they were underused. User convenience and household preferences, which traditionally have often been neglected in the design of rural water interventions, emerged as the fundamental issues to be addressed for programme improvement (Kolb deWilde et al., 2008). Gill and Flachenberg (2015) conducted a survey of hand-dug wells in Tanzania and found that the sustainability of the water points seemed to increase when the number of users per well was higher which could indicate that the more highly used water points are more valued by the community. Research by Hunter et al. (2009) showed that where improved community water supplies were unreliable and prone to interruptions, risk of infection was significantly greater on days that people had to revert to untreated water consumption. They also proposed that exposure to only a few days of untreated water consumption resulted in the loss of the annual health benefits attributed to consumption of water from an improved supply. Majuru et al. (2011) confirmed this, observing that while the implementation of improved water systems appeared to be associated with a reduction of diarrhoeal disease in communities, the health impact was most obvious where systems were reliable. They