Feasibility of a Flow Solar Water Disinfection System

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Abstract- Solar water disinfection (SODIS) is a household water treatment (HWT) method that utilises energy from the sun to kill pathogenic microorganisms in drinking water stored in small transparent containers and exposed to about 6 hours of strong sunlight. The study investigated the feasibility of a prototype continuous-flow SODIS system fabricated with locally available materials. The prototype system was operated for two weeks under varying water turbidity, microbial contamination, and retention time so that the performance of the system could be assessed. Analyses of samples collected from the inlet and outlet of the system showed that retention time is critical. One-day retention time achieved complete bacterial inactivation 60% of the time, while a 2-day retention time achieved complete bacterial inactivation 100% of the time, regardless of weather and the inlet water quality. The system was found to be a technically and economically viable alternative capable of stimulating uptake, diffusion, and sustained use of SODIS when compared to other continuous-flow SODIS systems developed in the past. However, interactions with potential end-users revealed that a massive promotion campaign and enlightenment programs would be required to make HWT a mainstream practice in developing countries.

Keywords: Solar disinfection, Drinking water, Diarrhoea, Faecal coliform, Flow reactor

1. INTRODUCTION

Drinking water contaminated with microbial pathogens is a major transmission route for diarrheal diseases. Approximately 760,000 young children die annually from the symptoms of diarrheal disease, most of them in low- and middle-income countries (Luzi et al., 2016). Figures from coverage estimates suggest that Nigeria is the foremost contributor to these deaths with more than 80,000 deaths yearly due to lack of access to safe water and adequate sanitation (UNICEF, 2020; WHO & UN-Water, 2014). About 88% of these deaths can be prevented by improving water quality at the point of use (Black et al., 2003).

Among the point-of-use and household water treatment options (boiling, chlorination, and filtration) one promising technology that has gained popularity in the recent decade is Solar Water Disinfection (SODIS). SODIS procedure is simple: fill small transparent containers (usually glass bottle or polyethylene terephthalate – P.E.T bottles) with water of doubtful microbial quality and expose them to direct sunlight. The heat and ultraviolet components of solar radiation drive a series pathogen inactivation processes to produce water that is microbiologically safe to drink after about 6 h of exposure to strong sunlight (Acra et al., 1989; Joyce et al., 1992). SODIS has been shown to reduce the incidence of diarrhoea and other infectious diseases in many places around the world (Sobsey, 2002). SODIS methods are recognised by World Health Organization (WHO) as one of the household water treatment and safe storage (HWTS) options, especially for the treatment of water in emergencies where people do not have access to alternative methods of obtaining safe drinking water. Concerns about the migration of genotoxins and other potentially harmful chemicals into SODIS water during exposure had been addressed through numerous control experiments (McGuigan et al., 1998; Schmid et al., 2008; Ubomba-Jaswa et al., 2010). The balance of evidence from these studies suggests that the risk is the same for everyone consuming bottle water with or without solar exposure (Luzi et al., 2016). More than 5 million people in over 55 countries were using SODIS for their daily water disinfection as of 2016 (Luzi et al., 2016).

The objective of the present study is to assess the feasibility of a flow SODIS, designed and fabricated by the authors. The flow SODIS was named PET-in-series SODIS (PIS-SODIS) in this paper for ease of reference and to reflect the fact that it was made of PET bottles connected in series. The purpose of PIS-SODIS and other prototype flow SODIS developed in the past was to remove some of the inherent drawbacks of conventional SODIS, namely small treatable volume, high labour demand involved in handling so many bottles, and the potential for under-exposure and misapplication of the method (Flores-Cervantes, 2003; Loux, 2005). PIS-SODIS was designed and operated to address these drawbacks and also to improve on simplicity, cost, and sustainability, which are the essential attributes of a typical household water treatment system.

2. MATERIAL AND METHODS

Figure 2.1 (a) shows the schematic diagram of the prototype SODIS system depicted in Figure 2.1 (b). The prototype system consists of oxygenation, filtration, sedimentation, and disinfection units. The oxygenation tank is an inverted 19 L plastic (polycarbonate) water dispenser bottle. The mouth of the dispenser bottle is in direct contact with the water in the filtration funnel so that water level in the funnel is maintained by automatic replacement as soon as it reduces below the mouth of the dispenser bottle. Thus, bubbles of air are allowed into the dispenser bottles, thereby oxygenating the water. Oxygenation is important because the germicidal action of SODIS is known to depend on the level of dissolved oxygen (Reed, 1997).

The system was also designed to provide multiple barriers to the colloidal particles that are responsible for turbidity in water. Firstly, the funnel is stuffed with a filter cloth so that filtration takes place before the water enters the sedimentation basin. The outlet valve of the sedimentation basin is placed at a level higher than the inlet mouth of the funnel so that particles that escaped the filtration unit could settle out under the quiescent condition of the sedimentation basin. Further turbidity removal is expected inside the disinfection unit. This happens when the velocity of flow reduces below the terminal velocity of the colloidal particles as the water enters the disinfection unit, allowing the particles to settle.

Turbid water was prepared by addition of dust and soil to the test water until the required turbidity was achieved. This solution was then sterilised by autoclaving for 15 min at 120 p.s.i and allowed to cool before the water was seeded with faecal coliform. Water turbidity was measured with a standard turbidity tube (DelAgua; manufactured by the Robens Institute, Guildford, UK).

The disinfection unit consists of solar reactors (PET bottles) connected in series using a flexible Polyvinyl chloride (PVC) tubing system. The reactors are 1.5 L PETs perforated at the bottom and the top cork to enable tubing connections. Before tubing, plastic tips/connectors made of silicone rubber would be inserted in the orifice to prevent leakage. Silicone rubber and PVC were chosen because of their perceived thermal stability. The top corks of the inlet and outlet PETs also featured catheter connectors that allowed the standard mercury thermometers to be fitted without leakage.

The retention time is controlled by the rate by which water is withdrawn from the clean water reservoir. The system is arranged so that as soon as water is withdrawn from the clean water reservoir, flow is instantaneously initiated by water level difference between the sedimentation basin, which drives the flow and water level in the clean water reservoir. As long as the average rate at which water is withdrawn from the clean water reservoir is less than the desired flowrate, every slug of water that entered the disinfection unit will stay for a period longer than the theoretical retention time.

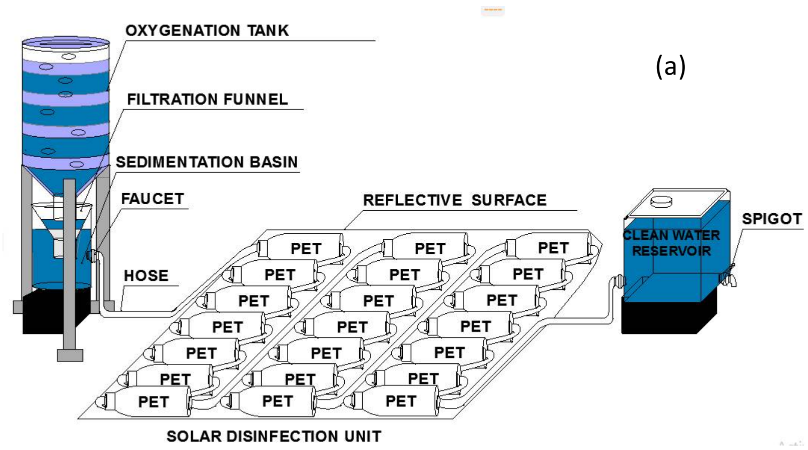

Figure 2.1: (a) A schematic diagram of PIS-SODIS; (b) a pictorial diagram of the prototype PIS-SODIS

Between 1 and 2 hours before the experiment, a batch of water would be contaminated with 2 – 5 % fresh clarified sewage obtained from the University of Nigeria, Nsukka sewage treatment pond in order to maintain the population of faecal coliform within a realistic concentration. The set-up was operated for 2 weeks in May 2019. The system was allowed to flow for a period equal to the theoretical retention time before samples were taken daily from the inlet and outlet for faecal coliform count. The inlet samples were taken from the funnel before the water is filtered, after oxygenation. Temperature readings were taken from the mercury thermometers fitted to the inlet and outlet PET reactors. The retention time was calculated from the flow rate and total volume of the reactors. Irradiation intensity data were obtained from the weather station of the National Centre for Energy Research and Development (NCERD), Nsukka located about 300 m from the site of the experiment.

3. RESULTS AND DISCUSSION

Table 3.1 shows the operating conditions of the PIS-SODIS together with the faecal coliform removal efficiency. The retention time proved critical. One-day retention time achieved complete bacterial inactivation 60% of the time, while a 2-day retention time achieved complete microbial inactivation 100% of the time, regardless of weather and the inlet water quality.

Table 3.1: Efficiency of PIS-SODIS in removing faecal coliform

Date	**Flow rate (L/day)**	**Retention time (days)**	**5 h peak radiation intensity (W/m^2)**	**Max. water temperature**	**Inlet (MPN/100 ml)**	**Outlet (MPN/100 ml)**	**Efficiency (%)**
8/5/2019	16.50	1	419.4	43	800	93	88.38
9/5/2019	16.50	1	770.1	55	> 1100	< 3	< 99.73
11/5/2019	16.50	1	551.5	50	240	< 3	< 98.75
12/5/2019	16.50	1	228.1	34	460	240	47.83
13/5/2019	16.50	1	586.3	52	240	< 3	< 98.75

14/5/2019	8.25	2	360.1	41	460	< 3	< 99.35
15/5/2019	8.25	2	456.9	45	> 1100	< 3	< 99.73
16/5/2019	8.25	2	505.3	49	210	< 3	< 98.57
17/5/2019	8.25	2	458.0	46	> 1100	< 3	< 99.73
19/5/2019	8.25	2	653.6	54	90	< 3	< 96.67

Table 3.2: Efficiency of PIS-SODIS in removing turbidity

Date	**Flow rate**	**Retention time (days)**	**Inlet**	**outlet**	**Efficiency**
8/5/2019	15	1	55.4	6.6	88
9/5/2019	15	1	43.6	4.4	90
11/5/2019	15	1	57.3	5.7	90
12/5/2019	15	1	36.7	7.0	81
13/5/2019	15	1	46.8	6.1	87
14/5/2019	7.5	2	64.9	3.2	95
15/5/2019	7.5	2	49.1	3.4	93
16/5/2019	7.5	2	39.2	4.3	89
17/5/2019	7.5	2	51.4	4.1	92
19/5/2019	7.5	2	37.0	2.2	94

The maximum water temperature of the outlet reactor was, on average, 2.5 ^{o}C higher than the inlet reactor. The system also performed well in turbidity removal. Table 3.2 shows the turbidity values of the raw water and the water collected from the clean water reservoir. The system was able to reduce the raw water turbidity to below or close to the WHO’s standard of 5 NTU (WHO, 2011). There was a significant increase in the turbidity removal efficiency when the average flow rate (or average water withdrawal rate) was reduced from 15 l/day to 7.5 l/day (student t-test $p = 0.02$).

The economic feasibility of the system was assessed by comparing the cost of PIS-SODIS with the cost of two previously developed household-scale continuous-flow systems, namely SC-SODIS and Spirasol developed by Flores-Cervantes (2003) and Loux (2005), respectively. Table 3.3 shows the cost comparison of PIS-SODIS, Spirasol, and SC-SODIS. Deductions from the total cost revealed that the PIS-SODIS is 3.2 times cheaper than Spirasol and 5.6 times cheaper than SC-SODIS.

To assess the social acceptability of PIS-SODIS, the authors invited six officials from the Enugu State Water Cooperation and School of Public Health, Nsukka to introduce them to PIS-SODIS and gauge their perception of the system and its chance of diffusing into the community. They confirmed the taste of PIS-SODIS water to be good, with no discernable odour. Again, the officials that were invited to drink the PIS-SODIS water could not distinguish when they were made to drink sachet water or PIS-SODIS water at random. They also agreed they could go to the border of arranging PIS-SODIS to ensure the safety of their drinking water if no other methods are available.

Table 3.3: cost comparison of some prototype continuous flow SODIS systems

PIS-SODIS		Spirasol		SC-SODIS	
PET Plastic Bottles × 8	Free	PVC Tube (20 ft.) × 1	$21.50	PET Plastic Bottles × 8	Free
0.2 cm flexible tubing × 8	$3.29	$^1/_4$” PVC Ball Valve × 1	$2.94	$^1/_4$” PVC Ball Valve × 1	$2.94
Funnel × 1	$0.82	Silicon Caulk × 1 tube	$2.99	$^3/_4$” PVC Pipe × 10 ft	$7.50
Filter cloth × 1	$1.10			$^3/_4$” PVC 4-way fitting × 2	$1.38
Plastic connector × 24	$3.29			$^3/_4$” PVC T fitting × 1	$0.98
				$^1/_4$” PVC 90^0 bend × 4	$1.56
				$^1/_4$” Zinc pipe-to-hose converter × 8	$28.42
				Silicon Caulk × 1 tube	$2.99
				Plumber’s Tape × 1 roll	$0.99
				Glue sticks × 1Pack	$0.99
Total	$8.50		$27.43		$47.75

$1 = ₦361 (May, 2019)

The most alarming responses were received when some women from a close-by village were invited to have their take on the system. When they demanded to know the purpose of the setup and the authors explained. The authors further delved into the scourge of diarrhoeal disease among under-5 children. In response, the women played down the need for such a system, telling the authors that they do not get sick by drinking the water from their village stream, yet they have no such treatment systems. When the authors made vigorous effort to connect the prevalence of under-5 diarrhoea death with the consumption of microbially contaminated water, the women, almost in unison, dismissed the claimed and retorted that such diarrhoea deaths result from the illnesses of teething. The women’s response reflects a deep-seated misconception that pervades rural communities of developing countries. Therefore, for household water treatment to become a mainstream practice, massive promotion campaign and enlightenment programs would be required to dispel certain misconceptions about the connection between untreated water, teething, and infant diarrhoea.

4. CONCLUSION

The ease of fabrication and operation, together with the water quality improvement capacity of PIS-SODIS confirmed it as a feasible water treatment option suitable for developing countries with abundant solar energy resource. Two-day retention time is ideal for the operation of PIS-SODIS. However, this retention time may have to be increased, especially during cloudy and colder months of July and August when the weather is incessantly rainy and overcast. Despite the promise of PIS-SODIS, much work still needs to be done on removing the cultural and behavioural factors militating against the uptake and sustained use of SODIS. Such cultural barriers could be dismantled through promotional campaign and enlightenment programs on the health benefit of point-of-use water treatment.

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