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Assessment of the 20L SODIS bucket household water treatment technology under field conditions in rural Malawi

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A R T I C L E I N F O

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A B S T R A C T

Two billion people worldwide consume unsafe drinking water. The problem is particularly pronounced in Sub-Saharan Africa, where more than a quarter of the population relies on unimproved surface water sources. Based on the principles of solar water disinfection (SODIS), a new household water treatment technology, the SODIS bucket, was developed to improve the microbial quality of water from these sources based on controlled tests in a laboratory setting. This study set out to evaluate the efficacy of the technology in a field setting, in rural communities in the Chikwawa District in southern Malawi.

SODIS experiments were carried out in two different vessels (1-L PET bottles and 20-L polypropylene SODIS buckets), over three months using unprotected water sources normally used by community members. Vessels were exposed to direct sunlight for 8 h per day in a village setting and were sampled at regular intervals to determine total coliforms, *E. coli*, turbidity, UV transmittance and UV dose.

In these experiments, the SODIS bucket reached inactivation targets for *E. coli* (<1 CFU/100 mL) in two of seven experiments and for total coliforms in one of seven for total coliforms (<50 CFU/100 mL), despite having greater UV doses than were seen in the evaluation carried out under controlled conditions during the bucket's development. PET bottles reached inactivation targets for both *E. coli* and total coliforms in five of seven experiments. There was no single factor that could be identified as preventing adequate inactivation, but the role of organic matter, inconsistent nature of the water source, and vessel size, when coupled with organic matter, were identified as contributing factors. This study highlights the need for further prototyping to provide a suitable pre-treatment step for unprotected water sources, and the importance of field testing with real-life parameters to ensure new technologies are context appropriate.

1. Introduction

Access to safe drinking water is essential to human health. Unsafe drinking water is estimated to cause 485,000 diarrhoeal deaths annually through the transmission of infectious diseases, of which up to 90% are children (WHO, 2019, 2007). Even when diarrhoea does not result in death it has long-lasting effects; delaying growth and development by reducing the intake of calories and nutrients. This puts at risk the 144 million people who are dependent on unimproved surface water sources such as rivers, lakes, ponds, and canals globally (UNICEF and WHO, 2019). In Sub-Saharan Africa, this problem is particularly pronounced, where 26% of the population is reliant on unimproved water sources (UNICEF and WHO, 2019), and inadequate Water Sanitation and Hygiene (WASH) has been attributed to 60% of all diarrhoeal deaths (Prüss-Ustün et al., 2019). Even improved water sources such as public taps, tube wells, protected dug wells, and rainwater systems are not always safe; two billion people use a drinking water source contaminated with faeces, or consume drinking water which has been subject to post collection contamination as a result of household storage (WHO, 2019; Wright et al., 2004). Therefore, a large proportion of the population does not have access to water which is safely managed as described in the United Nations Sustainable Development Goals (UN

Abbreviations: (HWTS), Household water treatment and safe storage; (LMICs), Low and Middle Income Countries; (PSA), Plataforma Solar de Almeria.

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SDG) framework; improved sources located on premises, available when needed, and free from faecal and priority chemical contamination (UNICEF and WHO, 2019).

In the absence of a piped water supply on premises, people in both urban and rural locations may use household water treatment and safe storage (HWTS) to improve and maintain water quality and thereby reduce the risk of waterborne diseases (Sobsey, 2002). To realise the full health benefits of improved water quality from HWTS, the technology must not only be effective, but users must treat their water continuously and consistently (Brown and Clasen, 2012; Enger et al., 2013). The effectiveness of HWTS is limited by user uptake and adherence to correct, consistent and sustained use, with one study finding that when HWTS use reduced from 100% to 90% of the volume of water consumed, the predicted health benefits, measured as disability affected life years, reduced by up to 96% (Brown and Clasen, 2012).

There are several factors that can affect uptake and continued use of HWTS in a community. Ojomo et al. (2015) identified 47 enablers and barriers to sustained and scaled HWTS use. These factors can be individual (the target households and their communities), or organisational (implementing organisations and governments) or both. Individual factors include user demand for a HWTS, preferences for certain types of technology, ease of incorporations into normal routine, and time taken to use the technology. Challenges shared by individuals and organisations include product supply of the HWTS systems as well as spare parts, and the provision of user guidance for households on the technical activities related to HWTS practices. Organisations must overcome difficulties collaborating with existing community programs, resource availability, and standardisation and certification of technologies (Ojomo et al., 2015).

To address some of the issues around standardisation and certification of technologies, the World Health Organisation (WHO) has developed a performance specification for HWTS systems based on health-based microbiological performance targets to choose an adequate system (WHO, 2011). The specification takes a tiered approach to performance targets defined across categories of highly protective systems, protective systems and interim systems (WHO, 2011). To date the WHO program has evaluated 30 proprietary HWTS products fitting into the categories of membrane ultrafiltration, ceramic filtration, flocculation-disinfection, flocculation bio-filtration, UV disinfection, chemical disinfection, and solar disinfection products (WHO, 2016, 2019a,2019b).

Solar disinfection of water dates to 2000 B.C.E. in ancient India. In modern times it has been studied as a treatment technology at least since the seminal work carried out by Acra and colleagues in the 1980s (Acra et al., 1980, 1984; Sobsey, 2002). Since then, researchers have further developed this technology into a viable HWTS technology in the form of the SODIS bottle system (McGuigan et al., 2012). The system consists of a 1- to 2-L plastic Polyethylene Terephthalate (PET) bottle left in the sun to absorb UV light. The primary mechanism of disinfection is UV inactivation, but there is also a synergistic effect provided by combining mild heat water temperatures with UV exposure (McGuigan et al., 2012). Field trials of the SODIS bottle have proven that, when used correctly, it can reduce rates of infant diarrhoea by up to 45% (Conroy et al., 1996; McGuigan et al., 2012). McGuigan et al. (2012) review of solar water disinfection technologies concluded that the SODIS PET bottle system is a proven technology.

In addition to PET bottles, research has been carried out using glass jars which are capable of transmitting 90% of UV-A radiation (Acra et al., 1980). However, glass bottles are heavy and pose a safety risk if they are broken (McGuigan et al., 2012). Plastic bags made of both PET (Walker et al., 2004) and low-density polyethylene (LDPE) (Dunlop et al., 2011) have both been trialled and can be more efficient than PET bottles as their shape can maximise the surface area of the water while minimising the depth of water for light to penetrate (McGuigan et al., 2012).

One shortcoming of the SODIS bottle system is the limited capacity of each bottle. The WHO advises that individuals need a minimum of 20 L of water per person per day for drinking and cooking (Reed and Reed, 2013). This makes use of small capacity bottles tedious and labour intensive. There have been previous attempts to develop larger volume vessels such as a 25-L borosilicate glass vessel in Kenya (Nalwanga et al., 2013) and 19-L polycarbonate water dispenser containers in Spain, Bahrain, and India (Keogh et al., 2015). Although both technologies were effective, neither has been implemented in the field at scale.

In rural Malawi, 13% of the population is dependent on unimproved water sources, with the remainder receiving a basic level of service from an improved source which is subject to post collection contamination (WHO, 2019). As such, there remains a significant need for effective HWTS in this setting, which must be cognisant of the enablers and barriers to uptake (Ojomo et al., 2015). Although the use of HWTS is supported through Malawi national water and environmental health policies, in practice this has tended to focus on safe water storage, and use of point of use chlorination during outbreaks of cholera to date (Rowe, 2012). As such, to examine the opportunity for a more sustained and affordable HWTS, a transdisciplinary method was used to develop a new, locally sourced, 20-L transparent polypropylene (PP) buckets, also known as the SODIS bucket (Morse et al., 2020). This design took into account not only the need for a greater volume of water but was also already familiar to users due to widespread use of plastic buckets, was low cost, required minimal maintenance, and minimized the impact on household chore time (Morse et al., 2020).

Controlled microbiological evaluation against the performance of already-proven 1.5-L PET bottles at Plataforma Solar de Almeria (PSA) in Spain showed the 20-L SODIS buckets were highly effective for solar disinfection of bacterially contaminated water and demonstrated similar inactivation kinetics to 1.5-L PET bottles therefore making them a good large volume alternative (Polo-Lopez et al., 2019). The objective of this study was to test efficacy of the SODIS bucket against standard SODIS PET bottles under field conditions and determine whether it should be further developed as a HWTS.

2. Materials and methods

2.1. Study area

Chikwawa District, in the southwest of Malawi, was selected by the WATERSPOUTT project (www.waterspoutt.eu) as the location to develop and field test the 20-L SODIS bucket system. Located in the Shire Valley, groundwater is highly saline in areas, making it unsuitable for domestic consumption (Monjerezi and Ngongondo, 2012). As a result, although groundwater boreholes are installed in several communities, many households still prefer to use unprotected surface water sources for drinking water. These sources have high levels of bacterial and faecal contamination making them unfit for human consumption (Pritchard et al., 2008). The water quality is also impacted by Malawi's tropical climate, with a hot and rainy season from mid-November to April and a cool and dry season from mid-May to mid-August. (Ministry of Natural Resources, Energy and Environment, 2020); consequently, the Shire Valley is extremely flood-prone at this time of year (DoDmA, 2015). This flooding disrupts the quantity and quality of water, and water access in the area (GFDRR, 2011).

Development and initial testing of the SODIS bucket began with a transdisciplinary study carried out by Morse et al. (2020). This study identified households from 17 villages (total population: 3290) within the district to participate in development and testing of the SODIS bucket prototype. Of the 46 water sources used in the villages, 27 were unimproved, characterised as: canal/irrigation channel ($n = 6$), river/dam/lake/pond/stream ($n = 5$) or unprotected dug well ($n = 16$). The 19 improved sources were characterised as: borehole/deep well ($n = 15$), protected dug well ($n = 1$), private/public tap ($n = 3$). With this in mind, the field study to test the efficacy of the SODIS bucket was nested within these participating populations.

2.2. SODIS vessels

SODIS experiments were carried out in two different vessels: 1-L PET bottles and 20-L PP SODIS buckets constructed locally in Blantyre, Malawi, to the same specification as the SODIS buckets used by Polo-Lopez et al. (2019). The key differences between the PET bottles and PP SODIS buckets were the container material properties and the vessel dimensions. PET transmits a greater total amount of UV radiation than PP, but this radiation is restricted to the UV-A and visible light wavelengths, as it is effectively opaque to UV-B radiation (Polo-Lopez et al., 2019). PP transmits less total radiation but includes transmission of more lethal UV-B radiation (Polo-Lopez et al., 2019). The other factor to consider, the vessel size, affects the optical path length through water in the vessel. Vessel dimensions are shown in Fig. 1. The vessel size becomes relevant when you consider that the light attenuating effect of natural waters increases exponentially with water depth (Kirk, 2010).

Fig. 2. Experiment set up A locally made table, UV photometer is shown on the ground.

2.3. Experimental methods

The experiments were carried out in Malawi between October 28, 2019 and January 25, 2020 and consisted of two phases. In phase one, 16 of the 46 unprotected water sources were examined to determine the water matrix characteristics and the levels of microbial contamination of each source. Characteristics examined were, temperature, UV_{254} transmittance (filtered and unfiltered), turbidity, and *E. coli* concentration. From this assessment, four sites were selected for use in the remainder of the study. The criteria for selection were having a turbidity below 30 NTU, and ease of access to the site.

In phase two, the SODIS buckets and PET bottles were assessed concurrently. Water for the experiment was taken directly from sources in a single 20-L bucket that was distributed evenly across four 20-L SODIS bucket until each was full (80-L total). One of the buckets was then used to fill 15 x 1-L PET bottles. A schematic of the different number and type of vessels in each experiment is shown in Fig. 1.

The bottles and buckets were arranged on a table, made by a member of the village, to mimic the conditions used by the households in the study group (Fig. 2). The table was set up in a location approved by the village chief, and the vessels were exposed to natural UV radiation. The experiments began between 7am and 8am and ran for 8 h.

Although the objective of the research was to assess the effectiveness of solar water disinfection using SODIS buckets, carrying out experiments in PET bottles provided a benchmark for its performance to be assessed against. The effectiveness of SODIS in PET bottles has been well documented in both laboratory and field conditions (Joyce et al., 1996). Comparing the effectiveness of a solar water disinfection technology to that of SODIS in PET bottles is a common practice that has been used in several contemporary studies (Castro-Alfarez et al., 2017; Keogh et al., 2015; Lawrie et al., 2015) including Polo-Lopez et al. (2019) that studied the effectiveness of SODIS buckets under controlled conditions.

A dark control SODIS bucket and three dark control PET bottles were also included in the experiment to determine if inactivation of bacteria was occurring independently from UV exposure. These controls used the same water as the SODIS experiments and were stored in a shaded area and covered with a cloth bag. This inhibited UV exposure and helped to maintain an ambient temperature equivalent to water stored inside a home in the same location.

2.4. Sampling methods

After homogenization of source water, three samples were taken from a bucket at t = 0 h to determine the initial total coliform and *E. coli* concentrations. Samples were taken from PET bottles at 2-h time steps but only at 4, 6 and 8 h for SODIS buckets. At t = 8 h samples were taken

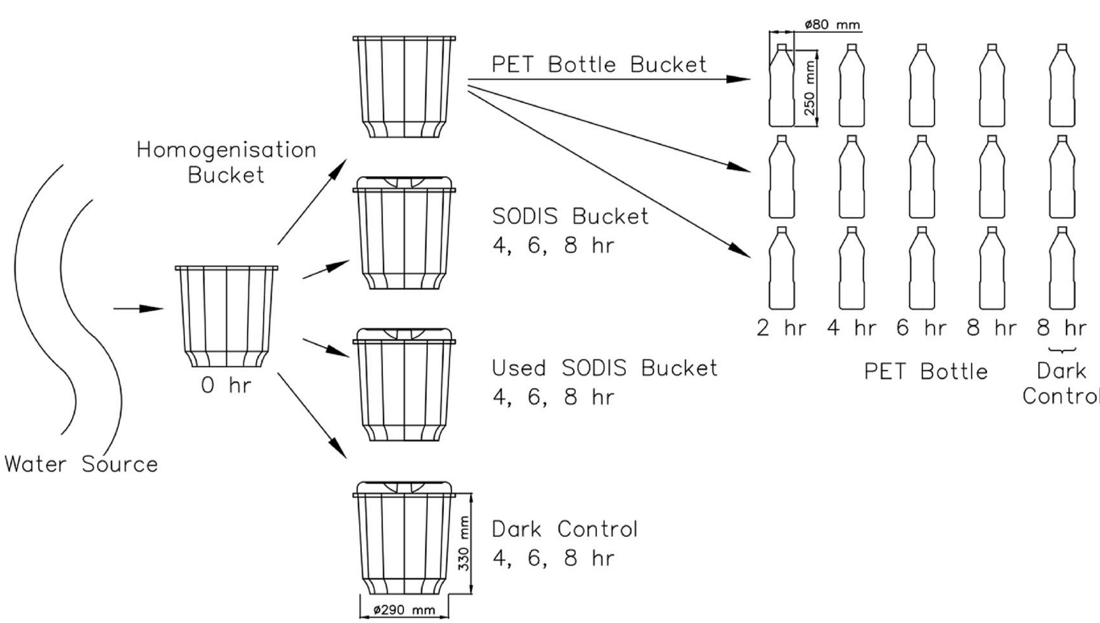


Fig. 1. Method Setup Schematic of homogenization process, experimental set up and vessel sizes.

from the three dark control bottles and the dark control SODIS bucket. For both PET bottles and SODIS buckets, samples were collected in triplicate with samples from PET bottles collected from three different vessels and for the SODIS buckets, the three samples were collected from the same vessel. The details of the sampling schedule are shown in a table in the supplementary material.

Before sampling, particles in the water were resuspended by either shaking for PET bottles or stirring with a sterilised instrument for SODIS buckets. Samples were put on ice in a cooler and were refrigerated within 12 h. The testing of physical and chemical parameters of the water matrix were carried out on site at the time of sampling.

2.5. Inactivation targets

In Malawi, the maximum permissible level of faecal coliforms in drinking water is 50 CFU/100 mL, for *E. coli* this limit is < 1 CFU/100 mL (MBS, 2005) which is also the WHO guideline value for microbial water quality (WHO, 2011). To determine if the SODIS bucket system could achieve this level of inactivation, WATERSPOUTT had set treatment targets to below detection limits in 100 mL for *E. coli*. The duration of solar exposure recommended for SODIS to be effective was set as 6 h based on previous testing (McGuigan et al., 2012; Meierhofer and Wegelin, 2002; Polo-Lopez et al., 2019).

2.6. Analytical methods

E. coli and Total Coliform concentration was determined as most probable number (MPN) by enzyme substrate coliform test using the IDEXX Colilert™ 24-h system. Where coliform concentrations exceeded 2400 MPN samples were diluted between 10^{-1} and 10^{-3} to enable quantification. Tests were carried out within 24 h of field sampling.

Physical and chemical characteristics were measured in the field using handheld instruments. Turbidity was measured using a Wag-WT3020 turbidity meter (Wagtech). UV_{254} transmittance is a surrogate measurement for natural organic matter (NOM) (Cho et al., 2006; Crittenden et al., 2012) and was measured using a P254C UV Photometer (Trojan Technologies). UV transmittance was measured in unfiltered samples and also samples that had been filtered through 45-μm filter paper to differentiate between dissolved and undissolved NOM.

Solar water disinfection is dependent on both total UV dose as well as intensity (Ubomba-Jaswa et al., 2008). To normalize results for the different weather conditions encountered during each experiment, solar radiation was measured in the 290–390 nm band every 30 min using a handheld PCE UV-34 radiation detector (PCE group). The sensor was set up to be aligned to the path of the sun. Using the memory function, the maximum and minimum irradiance was recorded every 30 min. The mid-point between these two readings was considered the average irradiance intensity for that time step. At every reading, the sensor was realigned to face toward the sun again. The UV dose was calculated using equation (1), integral UV intensity over time.

$$UV\ Dose = \int_{t_1}^{t_2} UVIntensity\,dt \tag{1}$$

2.7. UV transmittance of used SODIS buckets samples

The optical properties of the plastic materials were evaluated by recording their transmission spectra with a UV–Vis–NIR spectrophotometer (Varian Cary 500, Palo Alto, California, USA). Three independent and replicated measurements of the plastic samples were considered.

2.8. Data analysis

Results from coliform testing were initially recorded as MPN/100 mL and then converted to log units for analysis. As the different water sources had varying *E. coli* concentrations, the results are shown in log units of *E. coli* concentration remaining rather than log removal as would be conventional in a controlled test where initial *E. coli* concentrations were the same. When determining the mean coliform count, statistically outlying results were removed. In statistical analysis there is value in including outliers and as a rule they should not be removed from a data set. The decision to remove outliers in this research was based on the small number (3) of samples to be tested for coliforms and the disproportionate effect one outlying result would have on the average of a sample. Outliers were determined using Tukeys 1.5 IQR rule (Tukey, 1977), equation (2) and equation (3). Data that remained after cleaning was then averaged and used for further analysis.

$$Upper\ Limit > Q_3 + 1.5 \times (Q_3 - Q_1) \tag{2}$$

$$Lower\ Limit < Q_1 - 1.5 \times (Q_3 - Q_1) \tag{3}$$

The students t-test was used to determine if the difference between two sets of measurement was statistically significant. This was calculated using the *t*-test function in Microsoft Excel. All tests were type two (unpaired, samples of equal variance). Where there was an expectation of the direction of change, such as an increase in temperature, a one-tailed test was used. Where there was no expectation of the direction in which a value would change, a two-tailed test was used. The level of significance was set at a = 0.05.

2.9. Ethical approval

Ethical approval for this study was obtained from the National Health Sciences Research Committee (approval number 1823) in Malawi.

3. Results

3.1. Source water quality characteristics

In phase one of this research 16 of the 46 water sources used by households in the study group were evaluated for their water quality characteristics. The results (Table 1) showed the water sources to have a high turbidity with 9 of 16 water sources having a turbidity of over 30 NTU. This is the recommended maximum turbidity for SODIS treatment (Meierhofer and Wegelin, 2002). UV_{254} transmittance varied from 92%–20% in unfiltered samples and between 94% and 46% in filtered samples. *E. coli* concentrations varied between 4 and 6,488 MPN/100 mL with a median of 588 MPN/100 mL indicating that the water sources used by the study group were contaminated with faecal coliform bacteria and required treatment before consumption. Four sources were selected for use in the subsequent phase of the study (highlighted in grey in Table 1). The criteria for selection are discussed in the experimental methods section.

During the phase two SODIS experiments it was found that the composition of the water matrix at the selected sources had changed since the assessment in phase one. This change was attributed to the inconsistent nature of open water sources, and the onset of the first rains of the wet season carrying sediment from runoff into surface waters. Chikwawa experiences extreme seasonal variation, with the dry season (May–October) having an average rainfall of 5 mm, and the rainy season (November–April) having an average of 13 mm with a peak average of 226 mm in January (Weatherspark, 2021).

At two locations, KUT-A and MAF-D, turbidity increased to over 300 NTU and 500 NTU, respectively. In all cases, there was a reduction in UV_{254} transmittance, to between −3% and −26% of the original measurement, indicating an increase in NOM in the water. Given the initial criteria for source selection included turbidity of less than 30 NTU, source KUT-A was abandoned before the first experiment. The change in water quality at source MAF-D occurred after the first experiment had

Table 1
Microbial and physical source water quality data for phase one.

Water source code	Temperature	Turbidity	UV_{254} transmittance unfiltered	UV_{254} transmittance filtered	*E. coli*
	[C]	[NTU]	[%]	[%]	[MPN/100 mL]
BIA-A	35	153	29%	83%	6,488
DZI-A	29	2	92%	92%	4
DZI-B	29	28	58%	74%	435
DZI-C	29	70	50%	81%	2,282
KUT-A	28	23	72%	81%	1,553
MAF-A	33	40	54%	80%	1,300
MAF-B	33	93	20%	46%	2,600
MAF-C	29	23	75%	90%	205
MAT-A	30	39	67%	83%	91
MUO-A	31	21	69%	85%	6
NAM-A	31	32	66%	92%	135
NYA-A	33	33	55%	68%	727
NYM-A	30	29	54%	62%	4,611
NZA-A	30	46	66%	92%	325
SAL-A	30	29	65%	94%	187
SAL-B	31	58	61%	93%	816

already been carried out and was abandoned for the second experiment. Both sources were replaced with alternative open water sources (KUT-B and MAF-E) with lower turbidity within the same village (Table 2).

3.2. **E. coli** *inactivation* ***in SODIS buckets and PET bottles***

E. coli removal in SODIS Buckets **and PET bottles** from all seven experiments is shown in Fig. 3. These experiments were carried out under different solar conditions and results have been normalised by plotting them against the cumulative UV dose over 8 h. The maximum and minimum 8-h cumulative UV doses were 1,367 and 742 kJ/m^2 respectively, while the average was 1,083 kJ/m^2. The maximum water temperature recorded was 50.6 °C in a SODIS Bucket and 50.3 °C in a PET bottle. PET bottles were on average 0.5 °C warmer than SODIS buckets when T = 0 recordings were omitted. In SODIS buckets only two of the experiments (02-MAF-D and 07-MUO-A) reached the inactivation target for *E. coli* of below detection. The lowest dosage required was approximately 450 kJ/m^2 in experiment 02-MAF-D. In PET bottles five of the seven experiments achieved the inactivation target in 6 h. Experiments 01-KUT-B and 03-NYM-A did not reach the target. Results from the dark controls showed a median change in *E. coli* MPN of 0.22 Log (SD 0.22) in PET Bottles and 0.25 (SD 0.25) in SODIS Buckets.

Total coliform removal in SODIS Buckets and PET bottles was measured in all seven experiments. Only one of the SODIS bucket experiments reached the inactivation target of 50 MPN for total coliforms at a UV dose of approximately 900 kJ/m^2 In PET bottles five of the seven experiments achieved the inactivation target at UV doses between 700 and 1350 kJ/m^2. Graphs showing the results are presented in supplementary material [S1].

A comparison of the inactivation of *E. coli* in SODIS buckets and PET bottles from experiments 06-NYM-A and 07-MUO-A are shown in Fig. 4. These examples are shown as they represent experiments where inactivation targets were met at both high and low total UV doses relative to the other experiments in the study. The SODIS bucket was less effective at inactivating *E. coli* in all seven experiments with an average difference in inactivation of 0.94 log ($p < 0.01$), at all comparable timesteps. For total coliforms, this difference was greater at 1.46 log ($p < 0.01$).

3.3. Comparison of new and used SODIS buckets

SODIS buckets that had previously been given to families within the study group for home water treatment were obtained and included in the phase two experiments and a comparison of inactivation in the used and new buckets was made in six of the seven experiments. For *E. coli* (Fig. 5), used buckets had an average reduction value of 0.01 log ($p = 0.88$) less than in new buckets at each timestep. For total coliforms, the average difference was greater at 0.09 log ($p = 0.04$) less at each timestep.

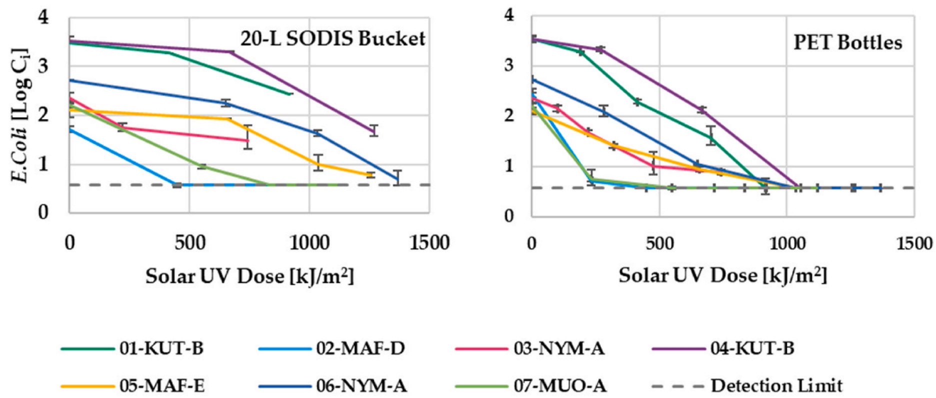
During the experiments it was observed that the used buckets and buckets used by villagers in the testing areas had an opaqueness to them caused by abrasion to the buckets surface. To establish if this opaqueness had an effect on the inactivation process samples of used buckets were tested for UV transmittance. The reduction in UV transmission by natural aging was measured in four used SODIS buckets (not those used in the SODIS bucket experiments). There is a noticeable difference in UV transmittance for the used buckets. The lowest for the 9-month-old samples, with values of 28.5% and 17.3% versus 33.3% and 33.8% for 6-month-old samples (Table 3). Samples from a bucket previously received were also kept in the dark as reference (sample 0 Months).

3.4. Factors influencing microbial inactivation

A comparison of *E. coli* inactivation in PET bottles for the two experiments carried out at water source KUT-B and NYM-A are shown in Fig. 6. These experiments were carried out using the same water source three weeks apart under different solar conditions. At water source KUT-B, (experiment 01 and 04) turbidity increased from 17 to 32 NTU between experiments but other water quality characteristics remained

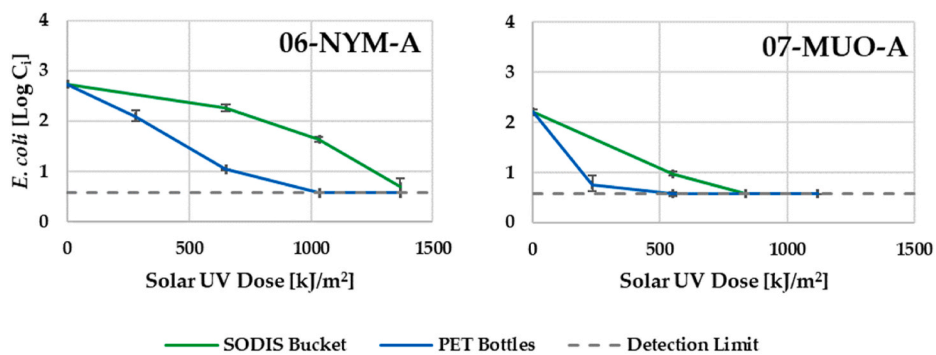
Table 2
Microbial and physical source water quality data for phase two.

Water source code	Temperature	Turbidity	UV_{254} transmittance unfiltered	UV_{254} transmittance filtered	*E. coli*
	[C]	[NTU]	[%]	[%]	[MPN/100 mL]
01-KUT-B	28	17	50%	58%	3,382
02-MAF-D	31	21	73%	87%	278
03-NYM-A	29	20	47%	58%	229
04-KUT-B	29	32	47%	63%	3,399
05-MAF-E	28	49	35%	65%	127
06-NYM-A	27	42	40%	57%	530
07-MUO-A	31	29	57%	77%	162



(a) (b)

Fig. 3. *E. coli* removal (a) SODIS buckets and (b) PET bottles in all seven experiments. Error bars indicate the standard error of the mean calculated from triplicate samples.



(a) (b)

Fig. 4. Comparison of *E. coli* inactivation in PET bottles and SODIS Buckets (a) 06-NYM-A and (b) 07-MUO-A. Error bars indicate the standard error of the mean calculated from triplicate samples.

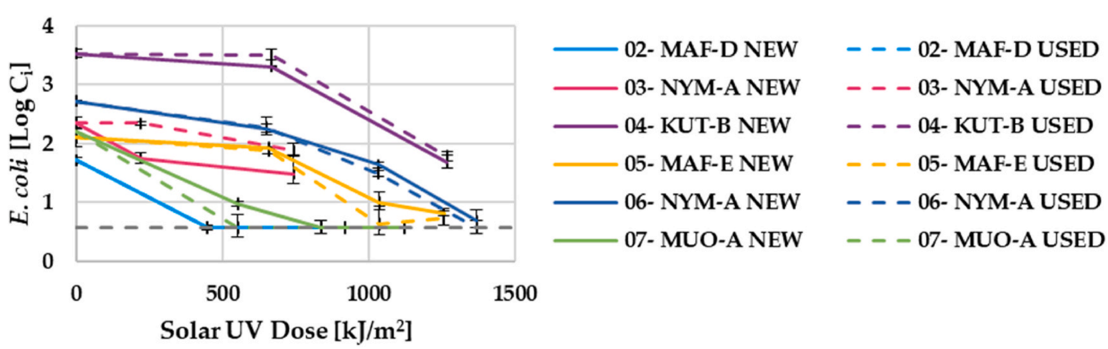


Fig. 5. Comparison of *E. coli* inactivation in new and used SODIS buckets New (solid lines) vs used (dashed lines) SODIS buckets in all experiments.

Table 3
Transmittance of samples from the buckets after solar exposure for 6 and 9 months.

	0 months	6 months	6 months	9 months	9 months
UV-A (%)	70.6	33.4	34.0	17.4	28.7
UV-B (%)	57.0	21.3	18.2	10.6	17.0
UV-C (%)	0.0	0.0	0.0	0.0	0.0

largely unchanged. UV intensity was higher in experiment 04 with a cumulative UV dose of 1,268 kJ/m^2 compared to 916 kJ/m^2 for experiment 01. At water source NYM-A, (experiment 03 and 06) turbidity increased from 20 to 42 NTU between experiments but as with KUT-B, other water quality characteristics remained largely unchanged. Here, the difference in UV intensity is more pronounced with experiment 06 receiving a cumulative UV dose of 1,367 kJ/m^2 compared to 742 kJ/m^2 for experiment 03. This difference in intensity is also evident in the maximum temperature of experiment 06 of 48 °C compared to 41 °C for experiment 03, while the difference was only 1 °C at KUT-B with 49 °C for experiment 01 and 50 °C for 04.

The relationship between cumulative *E. coli* inactivation and UV dose was compared and a strong correlation was found in both SODIS buckets, $R^2 = 0.83$ and PET bottles $R^2 = 0.88$.

The influence of turbidity in the source water, when inactivation is

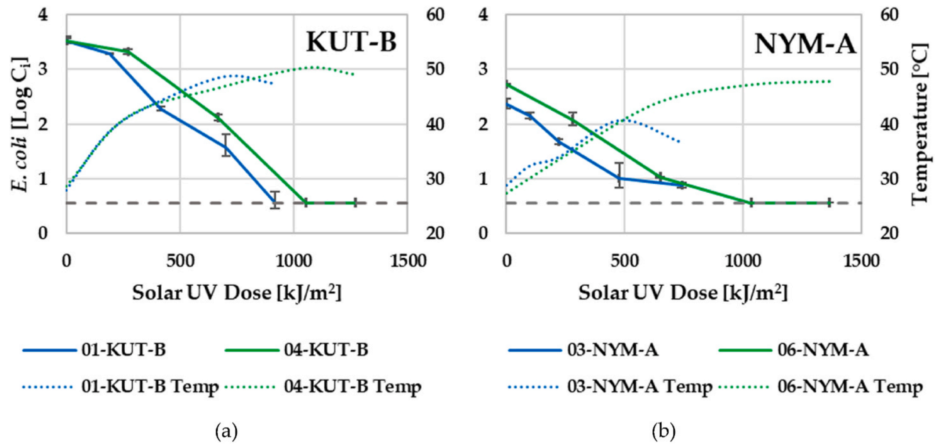


Fig. 6. Comparison of *E. coli* inactivation under different solar conditions PET bottles at water source (a) KUT-B and (b) NYM-A on two different days with different UV doses. Error bars indicate the standard error of the mean calculated from triplicate samples.

normalised to account for the different UV dose, has some correlation to *E. coli* inactivation in SODIS buckets, $R^2 = 0.63$, and almost no correlation in PET bottles $R^2 = 0.15$.

The amount of NOM (measured as UV_{254} transmittance) in the water is strongly correlated to inactivation of *E. coli* when inactivation is normalised to account for the UV dose both in SODIS buckets, $R^2 = 0.72$, and in PET Bottles, $R^2 = 0.80$.

4. Discussion

This study assessed the effectiveness of the SODIS bucket under field conditions to consistently meet the water quality standards laid down by the Malawi Bureau of Standards (MBS, 2005) and WHO (WHO, 2011).

We found that SODIS buckets were not able to consistently achieve the inactivation target that was set or replicate the results achieved under controlled conditions (Polo-Lopez et al., 2019). Although the experiments carried out in Malawi had much lower initial *E. coli* concentrations, median of 2.4 log compared to 6 log at PSA (Polo-Lopez et al., 2019)) we were still unable to reach complete inactivation even with much higher UV doses of 450–1350 kJ/m^2 compared to 250–300 kJ/m2 at PSA (Polo-Lopez et al., 2019).

Of the parameters measured in this study, the single biggest predictor of *E. coli* inactivation was total UV dose. However, it should also be kept in mind that inactivation occurs not only by UV oxidation of bacterial cells but also by the pasteurising effect caused by mild heat temperatures (McGuigan et al., 2012, 1998). Therefore, an increase in UV intensity, that increases water temperature, rather than an increase in duration of exposure is more beneficial to the SODIS process. The UV intensity for these experiments was typically higher at maximums of between 44 and 58 W/m^2 compared to a maximum of 28 W/m^{2}at PSA (Polo-Lopez et al., 2019). This would suggest that UV intensity was not the limiting factor in this instance. When we compare the results in PET bottles, the PSA evaluation achieved a 5-log reduction in *E. coli* with a UV dose of approximately 400 kJ/m^2. Again, it is difficult to directly compare the results in Malawi given the lower initial *E. coli* concentrations, but complete inactivation of *E. coli* required higher doses.

Previous studies have reported no observable difference in inactivation as a result of vessel volume ranging from 0.5 to 20-L systems, including controlled comparisons of the PP SODIS bucket with PET bottles (Gómez-Cuoso et al., 2012; Kehoe et al., 2001; Polo-Lopez et al., 2019). However, the results of this study showed a greater inactivation of *E. coli* occurring at the same UV doses in PET bottles compared to SODIS buckets. We attribute this finding to the attenuation of light as an exponential function of the photon path length through water. When high levels of NOM (measured as UV_{254} transmittance) are present, it follows that the SODIS bucket with a longer path length would be less effective than a smaller PET bottle with a shorter path length. These results would indicate that vessel volume does play a role in inactivation when NOM is present in high levels.

SODIS guidelines suggest a maximum turbidity of 30 NTU for successful water treatment (Meierhofer and Wegelin, 2002). Unlike many lab-based experiments, the water used in Malawi was taken from natural sources which vary in water quality characteristics not only from source to source but from day to day due to local weather events. In this study the initial turbidity was above this guideline in nearly half of the experiments, but although the effectiveness of the SODIS process tended to reduce with increased turbidity the correlation was not strong. Results from Kehoe, et, al. (2001) found that in high turbidity waters (>100 NTU) the UV dose required to achieve complete inactivation increased but was achievable with exposures of up to 8.5 h. They concluded that water above 300 NTU may need to be pre-treated by filtering or decanting to be treated effectively by SODIS. In light of these prior studies, and the results of phase one and two testing, which showed turbidity levels as high as 500 NTU in some water sources, shows that the issue of turbidity should not be set aside, but rather considered alongside other environmental factors such as concentration of NOM and solar conditions.

Published literature shows a large variability in experimental outcomes when different locations and water sources are used, and with a wide range of turbidity. Research carried out by Keogh et al. (2015) testing 19-L polycarbonate containers using low turbidity water at PSA, in Bahrain and India achieved a 4-log reduction of *E. coli* at UV doses of 250, 730 and 750 kJ/m^2, respectively. An additional test using high turbidity water (100 NTU) at PSA required 300 kJ/m^2 to achieve the same result. The water sources used in this study reflect the water sources available to the study participants, both in terms of the water quality and in the variability of its characteristics. These results show that although the SODIS bucket is effective in some situations, it is not a one size fits all HWTS solution. The effect of the variation in water quality can be mitigated by the use of pre-treatment devices such as the cloth filters developed by Morse et al. (2020). However, it should be noted that cloth filters are limited to removing particulate matter and will have limited effectiveness on dissolved or colloidal organic matter which in this study have been shown to have an effect in the larger SODIS buckets. Combining these two processes may increase the effectiveness of SODIS but may not be totally effective in all situations.

The effect of material degradation on the SODIS process was investigated by testing a used SODIS bucket alongside new SODIS buckets. Although the results showed that the new SODIS buckets had consistently lower *E. coli* counts at the same UV dose, this difference was of such a small magnitude that it appears to make no meaningful difference to overall treatment success. This conflicts with the measurement of light transmission through six-, and nine-month-old used SODIS buckets which found that UV light transmission through SODIS buckets reduced over time. It would be logical to expect this would lead to a reduction in UV transmittance and therefore inactivation effectiveness. The buckets being used by participants in the area had an opaqueness that had developed over time. Field researchers carrying out the experiments noted it was extremely easy to scratch the buckets if using anything abrasive to wipe the buckets clean between experiments. The samples that were tested for UV transmission were cleaned with sack cloth that could easily have abraded the surface. Despite there being little difference between the used and new buckets in this research, the effect of user cleaning methods should be investigated further as part of any future field trials.

A key objective of this study was to validate the relative efficacy of the 20L PP SODIS bucket in a real-life situation against that of both standard SODIS use, and results of the controlled testing of Polo-Lopez et al. (2019). The results clearly demonstrate that there was a high level of variation across water sources found within the field trial population, reflecting the diversity of water quality which changed not only by site and type, but also by day due to the influence of weather and use. This lack of consistency in water quality, compounded by the impact of user handling on the SODIS bucket demonstrates why it is so important to validate proposed water treatment systems through real-world field trial analysis. The value of assessing prototypes in their proposed settings cannot be underestimated to determine not only their scientific efficacy, but also unanticipated uses, practices and subsequent outcomes.

5. Limitations

Only five different water sources were used for experiments. This means that the data does not accurately reflect the full range and distribution of water quality conditions encountered by the trial group. Therefore, the results and conclusions that have been drawn are only applicable to water sources that fall within the range of conditions that were tested. This combined with the limited number of experiments means that the relationship between water quality characteristics and inactivation have limited statistical power. Although some of the correlations found in this study are strong, further experiments with a greater variance in individual characteristics are necessary to confirm these findings.

The methodology for this study was designed to assess the effectiveness of solar water disinfection. Therefore, the experimental methodology required that the effect of settlement in SODIS buckets be negated by resuspending settled particles before biological sampling. It is possible that SODIS could produce greater reductions in bacterial concentrations if the effect of particle settlement were considered.

Solar irradiances were measured directly, normal to the position of the sun. Ideally for the purpose of comparison with Polo Lopez et al. (2019), this study would have utilised a global pyranometer to also measure global irradiance. However, this equipment was not available, and it should be assumed that measurements of irradiance in this study are underestimates compared to the global irradiance.

6. Conclusions

The SODIS bucket did not consistently reach the bacterial inactivation targets, despite having greater UV doses than were seen in the initial controlled evaluation at PSA. No single factor could be identified as preventing adequate inactivation, but the role of organic matter and vessel size were contributing factors, whereas the role of turbidity did not have as great an impact as was expected. Future research should further examine the roles of organic matter and vessel size and should focus on the variety of conditions encountered in the real-world settings where SODIS is likely to be deployed. We would recommend that all proposed water treatment systems be tested in the environment in which they are intended to be used to ensure that they are fit for purpose.

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Data statement

Data for this study is available
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Author contributions

Steven Brockliss – Data curation, formal analysis, methodology, investigation, original draft.

Kondwani Luwe – investigation, review and editing.

Giuliana Ferrero – conceptualisation, funding acquisition, methodology, resources, supervision, validation, review and editing.

Tracy Morse - conceptualisation, funding acquisition, methodology, supervision, validation, resources, review and editing.

Declaration of competing interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2021.113913.

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