Evaluation of adaptive low cost solar water pasteurization device for providing safe potable water in rural households

Sharmin Zaman, Abu Yousuf, Anowara Begum, Md Latiful Bari and K. S. Rabbani

ABSTRACT

This study was conducted to evaluate the effectiveness of a simplified, low cost, pasteurization device in inactivating the diarrheal pathogens present in pond/lake/river water in order to provide safe potable water to people living in the rural areas of low resource countries. In this process, water in polyethylene bags was exposed to sunshine, where UV radiation emissions and heat absorption from the sunshine occurs simultaneously, and maintaining the heating at $<60\,^{\circ}C$, and minimum UV radiation emissions of 996.2 W/m^2 for approximately 30 minutes was found enough to inactivate diarrheal pathogens in water. The synergistic effect of heat, UV radiation emission and holding time causes the destruction of diarrheal pathogens. However, the performance of the device depends on the thickness of the insulation and the air gap between polyethylene bags. Regardless of sample sources, the highest population reduction of *Escherichia coli* observed in the bacterial challenge study was 6.8 ± 0.4 log CFU/ml. The physicochemical properties were found acceptable compared with USEPA potable water quality except turbidity, which is acceptable according to the BDS standard, and the shelf-life study results demonstrated that 6 months' storage of pasteurization device-treated water at room temperature is possible without compromising water quality. Therefore, this simplified pasteurization device could be useful in potable water-scarce areas of the world.

Key words | microbial count, pond/river water, potable water, solar pasteurization device, waterborne diseases

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INTRODUCTION

Access to safe drinking water is critical to human health and well-being. Providing safe, sustainable water supply to every household would yield optimal health gains and contribute to poverty reduction, economic development and environmental sustainability. Despite growing international attention to global safe-water access, poor water quality, sanitation and hygiene account for the deaths of approximately 525,000 children a year worldwide, mainly through infectious diarrhea (WHO 2017). Diarrheal diseases, which are frequently transmitted by contaminated water, are a leading cause of morbidity and mortality among children under 5 years of age in developing countries. Estimated annual total mortality from diarrheal diseases ranges from 2.5 to 3.5 million and more than 80% of these are children under 5 years of age (WWO 2010; Byrne *et al.* 2011). Like other developing countries, in Bangladesh, more than 25 million people lack access to safe water resources and

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most of these people live in rural Bangladesh (WHO/UNICEF 2013). This critical water situation involves the contamination of both ground water and surface water. The underground water between 20 m and 90 m is contaminated with arsenic because of human activities, and the surface water is contaminated every moment by human activities, industrial discharge, poorly constructed sewerage and water systems, lack of awareness and other activities, creating health problems leading to death (Jiang *et al.* 2012).

Investment in adequate safe-water supply or services in rural areas of developing countries remains low (IFC 2018). Currently, most investment in safe-water products and services in developing countries are aimed at middle- and upper-income people, who tend to live in urban areas, and have more safe-water awareness, higher income, access to electricity, and access to piped water or water treatment technologies. On the other hand, there has been little or no investment in remote and lower-income populations in these countries. These populations tend to be more rural and thus harder to access, and are usually less aware of the need for clean water or the availability of products to treat water (IFC 2018). They also have less disposable income and often no access to reliable sources of power or water pressure, hence are at greatest risk and therefore have the most need for effective and affordable options for safe drinking water.

Surface water including from a pond/river/lake is generally free from arsenic (Pandey *et al.* 2014) but highly contaminated with fecal material and highly turbid. Sari cloth filtration is very common to filter the collected pond or river water for household uses. This filtration may remove protozoa and cysts, but bacteria and viruses can pass through this filter; thus, usual practice is to boil the water for a few minutes, cool down to room temperature and then drink. Boiling water for several minutes effectively kills or inactivates most protozoa, bacteria, and viruses. However, this is very expensive for rural people as firewood is very costly, and widespread use of wood for water treatment would have a serious negative impact on the environment in Bangladesh where forest areas are greatly diminished.

Solar water purification is a simple, cheap, effective method of water disinfection and has gained in popularity. In this study, a low-cost, sustainable, solar pasteurization device was evaluated for its effectiveness in inactivating pathogens in water. The device is appropriate for household use in areas where access to safe drinking water is very difficult or for emergencies as a short-term, point-of-use water treatment after natural or man-made disasters. The device consists of a solar flat plate water heater which heats the water through the 'greenhouse effect'. The main advantages of this device are the ready availability of materials and ease of maintenance. In addition, the synergistic mechanisms of mild heat, UV radiation emissions and holding time were evaluated.

MATERIALS AND METHODS

Sample collection and preparation

Water samples were collected from the Shahidullah hall pond, Jagannath Hall pond, Bangla academy pond, Dhanmondi lake, Ramna lake, Shitalakshya, Padma, and Meghna river between 08.00 and 09.00, in 500 ml sterile bottles from approximately 4–5 cm beneath the surface of water, and transported to the laboratory in an insulated box within 1 hour, maintaining ambient temperature. The water samples were then filtered through fourfold to eightfold cotton sari cloths to remove the flocculants and contaminants and reduce the turbidity. This filtered water was then poured into transparent polyethylene bags and used for solar treatment. The initial bacterial count of filtered water was measured and recorded before being exposed to sunlight by using the low-cost pasteurization device.

Construction of the low-cost pasteurization device

The construction of the low-cost pasteurization device and its operating mechanism are explained briefly in Figure 1.

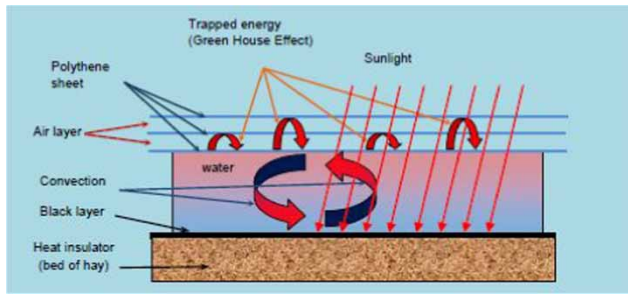


Figure 1 | Schematic of solar water pasteurization device mechanism.

The device has a thick base of thermally insulating material, typically made of straw. This was mainly to block heat loss through conduction below. On the top of the insulation, a bamboo tray was placed. The top surface of this bamboo tray was painted black. Alternatively, a black cloth or a black plastic sheet was spread on the tray. A transparent polyethylene sheet/bag was now spread over the tray into which water was poured to a depth of about 2.0 cm (Rabbani 2002; University of Dhaka 2011). The water was poured on to the polyethylene sheet or into polyethylene bags, depending on the availability of the materials (Figure 2). This allows water to come into intimate contact with the black surface below. The black surface absorbs solar energy, heats up and warms the lowest layer of water through conduction. The whole water layer was then heated through convection (Figure 1).

A second transparent polyethylene sheet was placed on the water surface in order to prevent evaporation of water which otherwise would condense on the transparent covers above. On top of this sheet, two transparent PVC sheets were spread leaving air gaps in-between. Spreading a few strands of straw in between the transparent layers prevents the plastic sheets from touching each other, thus maintaining air gaps. The air gaps provide insulation to prevent heat loss towards the top. The transparent covers and water allow visible and infrared solar radiation to reach the black surface below, which absorbs the energy and is heated. This in turn heats up the water as mentioned above. This heated water

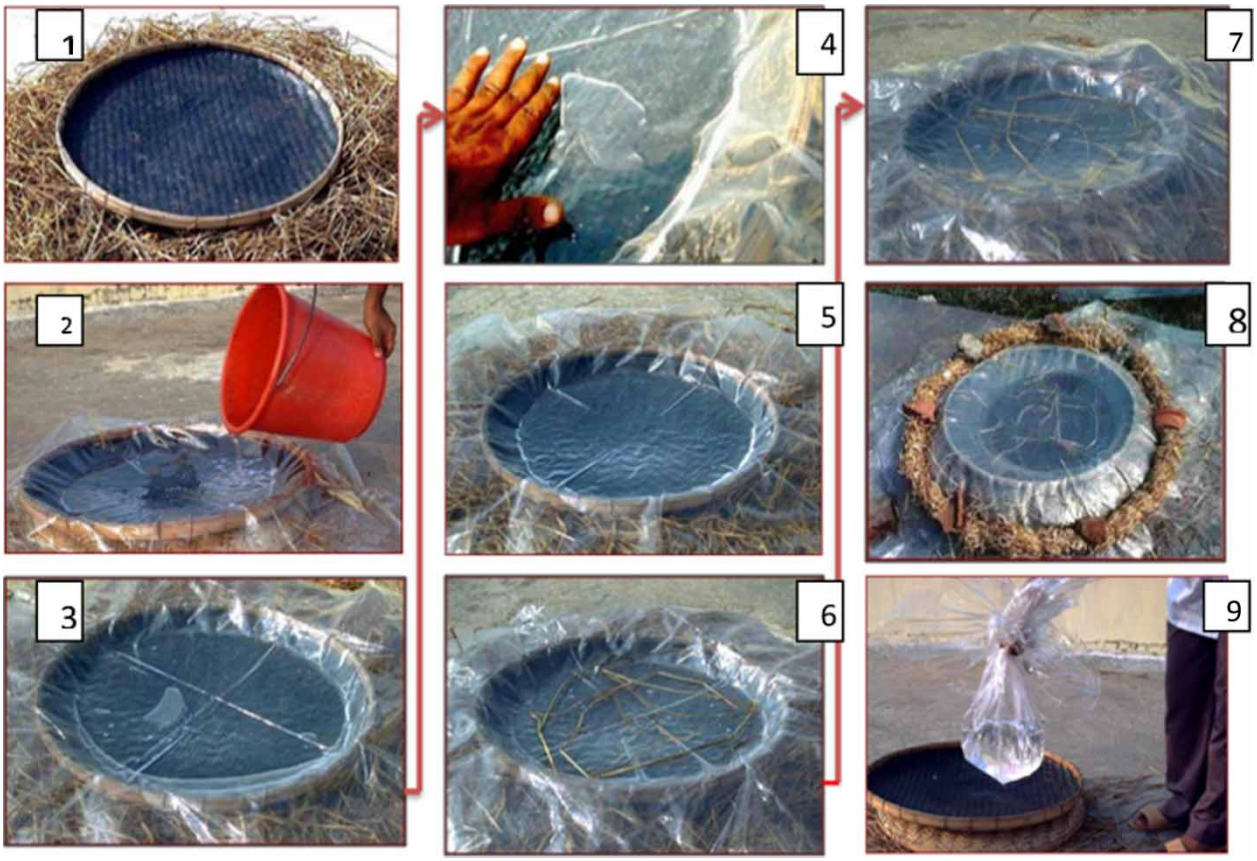


Figure 2 | Setting up the innovative low-cost solar pasteurization device: 1. Hay is spread to a thickness of at least 10 cm and the bamboo tray placed on it. 2. The water is filtered and/or sedimented to remove floating dirt and particles. A clean polyethylene sheet is spread on the tray and water poured to a depth of not more than 2 cm. The hay is adjusted to ensure the same depth of water on all sides. 3. A second polyethylene sheet is spread over so that it touches the water surface everywhere. 4. Air bubbles are removed to the sides by a light push with a finger (5). Otherwise water vapor will condense at the bubble and will block the sunshine. 6. A few strands of straw are spread over the sheet and the third polyethylene sheet is spread on top. 7. Similarly a few strands of straw are spread on the third sheet with the fourth and final sheet on top. 8. To keep all the sheets stretched out, some weights were put around the outside of the tray over the sheets. 9. After a prescribed time, the treated water is poured carefully into a storage pitcher or water tank.

then emits long wavelength infrared radiation, which is trapped by the transparent PVC cover above (Rabbani 2002). Since UV light passes through the water layer, water in a transparent bag was used which simplifies the process and only two transparent cover sheets are needed. However, the transparent sheets, particularly the polyethylene sheets can lose their transparency over time; therefore, these sheets may need to be changed frequently.

Solar insolation measurement

Solar insolation is defined as the amount of electromagnetic energy (solar radiation) incident on the surface of the Earth. Basically, that means how much sunlight is shining down on us. Thus, the solar insolation has significance for this solar water disinfection study. Based on solar radiation data collected from the Renewable Energy Research Centre at University of Dhaka and Bangladesh Meteorological Department, the maximum and minimum global radiation in Bangladesh could be defined. The maximum global radiation was recorded in April to May and the minimum in November to December (SWERA 2007). The geographic location of Bangladesh is 20°34′N to 26°38′N latitude and 88°01′E to 92°41′E longitude (OECD 2003). The country lies near the equator and hence the conditions to obtain sunshine are preferable and the solar radiation emissions are strong for 8 months of the year. The global horizontal irradiance (GHI), the total amount of shortwave radiation received from the sun on a horizontal surface, in Dhaka during March and April was measured as 722 W/m^2 and 764 W/m^2 (SWERA 2007). The total horizontal radiation is usually estimated as $S = 1{,}000$ W/m^2 on a clear day (Badescu 2008). The solar radiation emission measurements in this study were performed between March and April 2017 and took place in Dhaka at 23°43′N and 90° 24′E (Lundgren 2014).

During this time period, the zenith angle was measured as $Z = 20 - 23.5°$ and the diffuse radiation was estimated as $d = 200 - 350$ W/m^2. The total solar insolation striking the Earth's surface can be estimated using Equation (1) (Badescu 2008):

$$I = S \cos Z + d \quad (1)$$

The estimated value of the solar insolation in Dhaka during late March, when most outdoor experiments were done, was calculated as approximately $I = 1{,}139$ W/m^2 (Lundgren 2014). This value should be comparable with the solar radiation emissions during this study.

Solar disinfection experiment

The sari-filtered water was poured to a level of one-third of a transparent polyethylene sheet/bag (size 120 cm × 90 cm), so that the depth of water was up to 2.0 cm when the polyethylene bag was laid down on the blackened bamboo tray with the open end placed over the raised edge of the tray. The air bubbles were removed by lightly pushing with fingers. The devices were placed on the roof of the nine-storied building of the Centre for Advanced Research in Sciences of the University of Dhaka to get uninterrupted sunshine. To understand the synergistic effect of heat and UV radiation emissions on the destruction of microorganisms, an additional bamboo tray was used for shading the sunshine exposure and holding the heat at a certain temperature. In the spike study, the sari-filtered water was autoclaved and the bacterial inoculum was added to the filtered water so that the initial concentration of bacteria was 10^6 CFU/ml. The temperature and radiation emission intensity were continuously monitored and recorded using a temperature probe (LUTRON, Taipei, Taiwan) and Lux meter (INSTEK, KL, Malaysia), respectively.

Thermal inactivation experiment

Thermal inactivation of microorganisms in sari-filtered water samples was done using a temperature controlled water bath in the laboratory. Experiments were performed at different temperatures, 45, 50, 55 and 60 °C, using three replicates of 15 mL sterile containers with sari-filtered water and exposed to each temperature in a controlled water bath. Temperature was constantly monitored using a thermometer set inside the water bath. In the spike study, the water matrix selected for this work was autoclaved sari-filtered water, and the initial concentration of bacteria was 10^6 CFU/mL. Experiments were performed three times for each condition, showing high reproducibility (95% confidence level). The averages with standard deviation are shown in Tables 1 and 3.

Table 1 | Comparison of bacteriological quality and bacterial challenge study; physicochemical quality parameters of control and solar pasteurization treated water samples (pond, lake and river) with standard value[a]

Bacteriological quality indicators	Non-treated water samples (as control)			Treated water samples			USEPA std for drinking water (log CFU/ml)	BSTI std for drinking water (log CFU/ml)
	Pond	Lake	River	Pond	Lake	River		
	Mean value of bacterial populations (log CFU/ml)							
Environmental samples								
Total aerobic bacterial count	4.8 ± 0.4	4.1 ± 0.3	4.5 ± 0.1	1.3 ± 0.1	2.6 ± 0.2	0.8 ± 0.1	TT[3]	1,000
Total coliform count	4.20 ± 0.1	3.8 ± 0.2	3.8 ± 0.2	<1.0	<1.0	<1.0	NR	NR
E. coli count	3.8 ± 0.1	3.6 ± 0.1	3.1 ± 0.2	<1.0	<1.0	<1.0	NR	NR
E. coli O157:H7 count	3.4 ± 0.1	3.5 ± 0.1	<1.0	<1.0	<1.0	<1.0	NR	NR
Salmonella count	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	NR	NR
Vibrio count	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	NR	NR
Bacterial challenge test								
E. coli on TSAR	5.5 ± 0.3	4.5 ± 0.4	6.8 ± 0.2	<1.0	<1.0	<1.0	NR	NR
E. coli on SMACR	5.3 ± 0.2	4.4 ± 0.2	6.7 ± 0.1	<1.0	<1.0	<1.0	NR	NR

Physicochemical parameters

Parameters	Mean value of control samples	Mean value of treated samples	US EPA standard for drinking water	BDS standard
Color	Gray to yellowish (16–19 color unit)	15 (color unit)	15 (color unit)	5 (Hazen unit)
Odor	Odorous	Odorless	3 threshold odor number	Unobjectionable
Taste	Fishy-sour smelly	Agreeable	Agreeable	Agreeable
pH	6.9–7.7	7.1–7.6	6.5–8.5	6.4–7.4
Salinity (ppt)	0.1	0.1	0.1	0.1
Turbidity (NTU)	29.0–31.0	5.0–6.0	0.5–1.00	5.0
TDS	302–346	310–345	500	500
Conductivity μs/cm	600–780	620–690	NS	NS
BOD (mg/l)	2.1–2.5	2.71–2.76	5.0	5.0
COD (mg/l)	2.214–3.195	2.27–2.31	40	40
Iron (mg/L)	0.04	0.04	0.3	0.30
Manganese (mg/L)	0.02	0.02	0.05	0.50
Zinc (mg/L)	0.01	0.01	5.00	3.00
Lead (mg/L)	0.000	0.0004	0.015	0.01
Arsenic (mg/L)	0.002–0.003	0.002	0.01	0.05
Cadmium (mg/L)	0.00	0.00	0.005	0.003

[a]Detection limit: <1.0 log CFU/ml. TT[3]: treatment technique, a required process intended to reduce the level of contamination in drinking water; NR: not recommended; TSAR: tryptic soy agar with rifampicin (50 μg/ml); SMACR: sorbitol MacConkey agar with rifampicin (50 μg/ml); NS: not specified.

Bacteriological analysis

One hundred (100) ml of control, solar disinfected and thermal inactivated water samples were analyzed for total aerobic bacterial count, total coliform count, presence or absence of *Escherichia coli*, *Salmonella* spp., and *Vibrio* spp. according to USFDA Bacteriological Analysis Methods (2001). Both selective and non-selective agar media were used to identify the bacteria. tryptic soy agar (TSA, Fluka, USA) was used for total aerobic bacterial count, Hichrome^{TM} coliform agar (Fluka, USA) for total coliform count, sorbitol MacConkey agar (Oxoid, Hampshire, UK) for *E. coli*, bismuth sulfite agar (BD, USA) for *Salmonella* spp., and thiosulfate–citrate–bile salts–sucrose agar (TCBS, Nissui, Tokyo, Japan) for *Vibrio* spp. One hundred microlitres (100 µl) of serially diluted and non-diluted water samples were spread plated into each agar plate and incubated at 35–37 °C for 24–48 hours before presumptive colonies were counted. At least five randomly selected presumptive colonies of *E. coli*, *Salmonella* spp. and *Vibrio* spp. were isolated from selective agar and confirmed by biochemical test and API 20E kit (bioMerieux SA, Marcy-l'Etoile, France).

Physicochemical analysis

The physicochemical properties of treated and non-treated water including color, odor, taste, pH, turbidity, total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), conductivity, major metals (Fe, Na, Ca, Mg and Zn), and heavy metals (As, Cd, Cr, Pb) were analyzed according to the US EPA (2015) and BSTI (2001) standard methods.

Storage study

Treated water samples were stored at room temperature (25 ± 0.2 °C) in the dark and maintained for six months. Periodic bacteriological analysis was done at 7, 14, 21, 28 days, 3 months and 6 months of storage.

Bacterial spike study

Escherichia coli strains # CARS-2 (isolated from water) were cultured at 37 °C in 5 mL of tryptic soy broth (TSB; Oxoid, UK) medium supplemented with 50 mg/mL rifampicin (TSB-Rif). Cultures were transferred to TSB-Rifampicin using a loop at three successive 24-h intervals immediately before they were used as inocula. Cells were collected by centrifugation (3,000 × *g*, 10 min, 22 °C) and suspended in 9.0 mL of sterile saline water (0.85% NaCl solution). The inocula (9.0 mL) with an initial concentration of approximately 10^7 CFU/mL were maintained at 22 ± 1 °C and added to water samples within 1 h of preparation. Plating on media containing rifampicin greatly minimized the interference of naturally occurring microorganisms and facilitated the detection of test pathogen on recovery media. The isolated colonies were confirmed by detecting the *uidA* gene, specific for *E. coli*, using polymerase chain reaction (PCR) method.

Bacterial endotoxins test

The bacterial endotoxins test is an *in vitro* assay for detection and quantitation of bacterial endotoxins, a component of the cell walls of Gram-negative bacteria. The endotoxins detection was carried out by limulus amoebocyte lysate (LAL) test, using a lysate of amoebocytes isolated from the horseshoe crab (*Limulus polyphemus*) clotting reaction (US Department of Health and Human Services, Food and Drug Administration 2012). This reaction involves a coagulation cascade of sequentially activated proteases, which forms clots with endotoxin. Both the non-treated and treated water samples were tested for bacterial endotoxins as described by the LAL test kit instructions (Lonza, Valais, Switzerland).

Statistical analysis

All the trials were replicated five times. Reported data represented the mean values obtained from five individual trials, with each of these values obtained from duplicated samples. Data were subjected to analysis using the Microsoft Excel program (Redmond, Washington, DC, USA). Significant differences in plate count data were established at the 5% level of significance. For other data mean ± SD values are presented in Tables 1 and 3.

RESULTS

Effect of solar disinfection on physicochemical properties of sari-filtered water

Sari filtration is one of the common methods used by the rural people of Bangladesh to collect pond or river water for household uses. In this study, pond/river water was filtered with eightfold, used cotton sari cloths to remove the protozoa, zooplankton, phytoplankton and some bacteria or parasites attached to plankton. In addition, Colwell *et al.* (2003) reported that four-layer sari cloth removed more than 99% of *Vibrio* sp., from the pond/river water. Furthermore, in our previous study, results showed that fourfold or eightfold sari cloths generate a pore size of <40 μm and used sari cloth had a smaller pore size than that of new sari cloth, which was due to the softer and looser threads of the used sari (Zaman *et al.* 2017). In this study, the scan electron micrograph image of eightfold used cotton sari cloth showed a pore size of approximately 20 μm (Figure 3). Nevertheless, the sari filtration process is the cheapest way of removing turbidity from the pond/river water. The presence of higher turbidity provides protection to the microorganisms and obstructs the transmission of solar light, consequently limiting or interfering with the disinfection process; thus, sari filtration was done to reduce turbidity prior to solar disinfection. Turbidity values ranging from 29.0 to 31.0 NTU were observed in non-filtered pond/river water and these values were reduced to 9.0–11.0 NTU after eightfold sari filtration, and the turbidity values further reduced to 5.0–6.0 NTU after solar disinfection treatment (Table 1). Although the World Health Organization

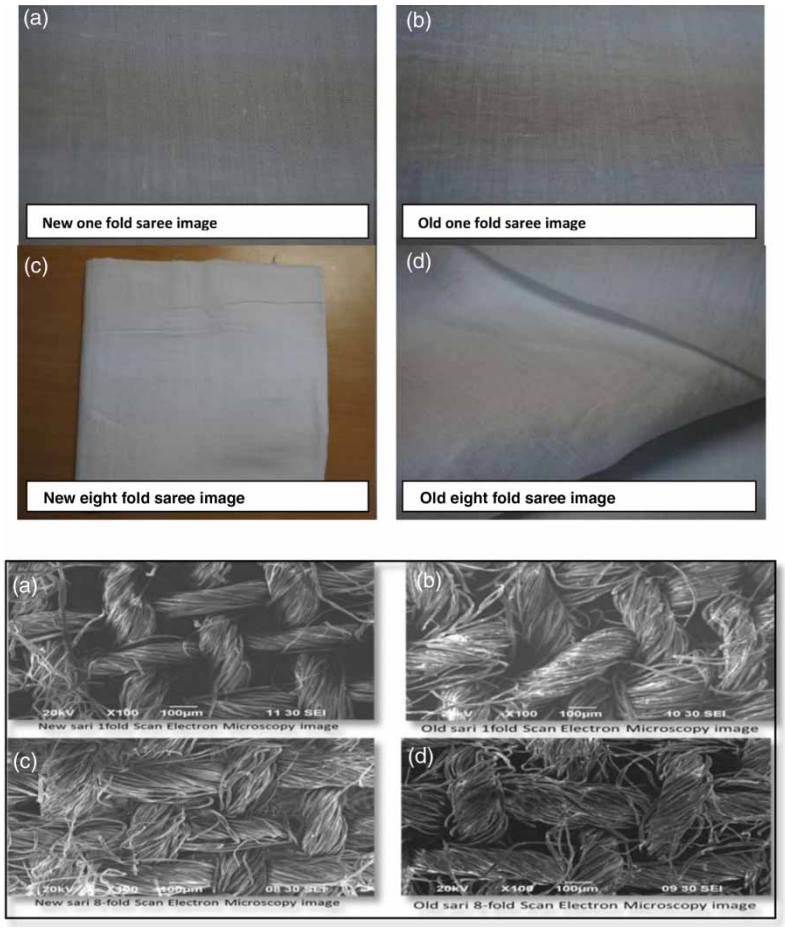


Figure 3 | Comparison of digital photograph and scanning electron micrographs of (a) onefold new sari, (b) onefold used sari, (c) eightfold new sari, (d) eightfold used sari cloths.

(WHO) standard turbidity value for drinking water is less than 1.0 NTU, the Bangladesh Standard Testing Institute's (BSTI) permissible turbidity value is 5.0 NTU, which was achieved in this study. Other physicochemical quality parameters including TDS, conductivity, BOD, COD, metal and heavy metal contents of the solar disinfection water were found within the acceptable limits (Table 1).

Effect of solar disinfection on bacteriological quality of sari-filtered water

The water-containing polyethylene sheets/bags were placed on the pasteurization device for a maximum period of 4 hours in the sunshine of a clear day. The sunshine exposure began at 9.30 or 10.00 and ended at 13.30 or 14.00 on the same day. This time period was fixed because of the higher solar insolation intensity which remained constant throughout the incubation period. Before and after this time period, the solar insolation intensity and heat generation intensity were lower. The initial water temperature was recorded as 30 ± 2 °C, and the initial solar insolation intensity was recorded as 1,373.02 W/m^2; the final water temperature after 4 h was recorded as 71.5 ± 2 °C and the solar insolation intensity after 4 h was recorded as 1,447 W/m^2 (Table 2).

The initial aerobic bacterial count, coliform count, *E. coli*, *Salmonella* and *Vibrio* sp. count of sari-filtered pond/lake/river water was recorded and the inactivation of pathogens after exposure to sunshine using the solar pasteurization device is presented in Table 1. Average aerobic bacterial counts of 4.1–4.8 log CFU/ml, coliform counts of 3.8–4.2 log CFU/ml and *E. coli* counts of 3.1–3.8 log CFU/ml were recorded in pond, river and lake water samples (Table 1). The presence of higher numbers of *E. coli* indicated that all the pond, river and lake water collected was contaminated with fecal materials. However, irrespective of water sources, *Salmonella* and *Vibrio* spp. were not observed in any of the sample analyzed throughout the study. When these water samples were exposed to sunlight using the solar pasteurization device, a significant reduction of aerobic bacterial counts was observed, while total coliform, *E. coli*

Table 2 | Relationship of temperature and solar insolation (W/m^2) in water exposed to sunshine in the pasteurization device

	Solar insolation (W/m^2)					
	Control	15 min solar	30 min solar	45 min solar	60 min solar	90 min solar
Temperature raised to 45 °C	1,373.02	ND	1,463.88	ND	1,443.94	1,462.99
Temperature raised to 50 °C	1,405.63	ND	926.11	975.03	ND	1,272.76
Temperature raised to 55 °C	1,401.43	1,497.68	1,561.91	1,594.42	ND	ND
Temperature raised to 60 °C	1,419.84	1,372.89	996.2	1,097.37	ND	ND

ND: not done.

Table 3 | Comparison of bacteriological quality of immediately treated and treated water with 6 months storage at room temperature (pond, lake, and river water)

	Treated water samples (immediate)			Treated water samples (6 months storage)		
Bacteriological quality indicators	Pond	Lake	River	Pond	Lake	River
Mean value of bacterial populations (log CFU/ml)						
Total aerobic bacterial count	1.3 ± 0.1	2.6 ± 0.2	0.8 ± 0.1	0.9 ± 0.1	1.1 ± 0.1	0.5 ± 0.1
Total coliform count	<1.0*	<1.0	<1.0	<1.0	<1.0	<1.0
E. coli	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
E. coli O157:H7	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Salmonella spp.	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Vibrio spp.	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

* < 1.0 = below detection limit; detection limit: <1.0 log CFU/ml.

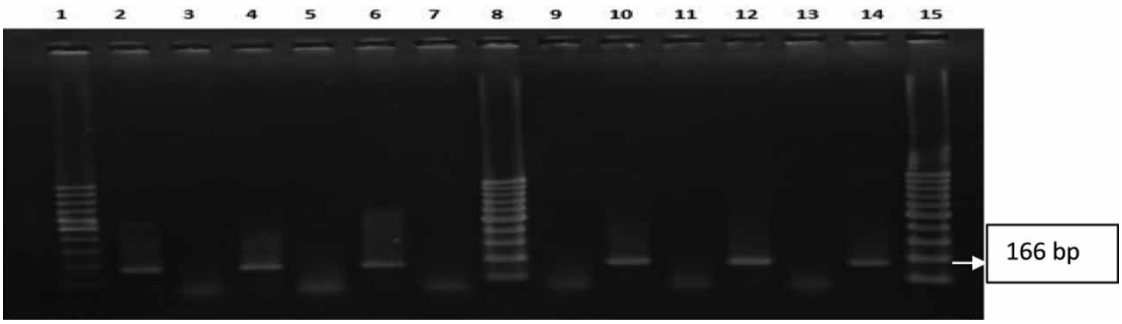


Figure 4 | Representative *E. coli* was confirmed by detecting specific *uidA* gene using the molecular PCR method. Lanes 1, 8 and 15 represent 100-bp standard DNA ladder; Lanes 2, 4, 6, 10, and 12 represent non-treated samples; Lanes 3, 5, 7, 9, and 11 represent treated samples; Lane 13 is the negative control; and Lane 14 is the positive control.

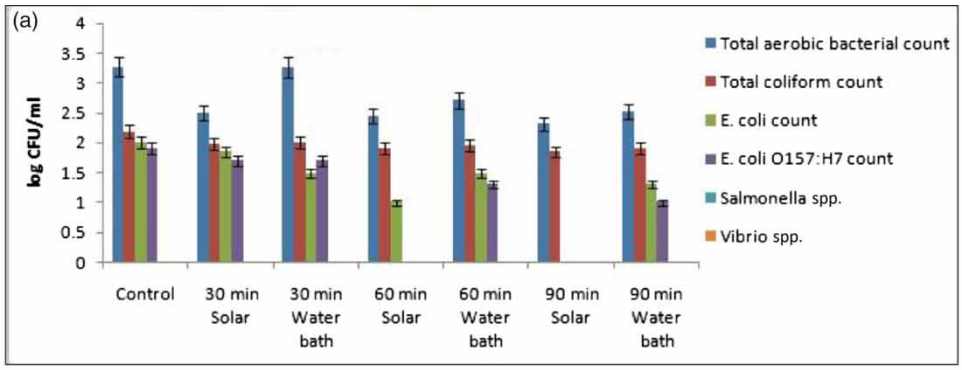
and *E. coli* O157:H7 were not detected. It is possible that total coliform, *E. coli* and *E. coli* O157:H7 were inactivated or severely injured and thus did not appear in the microbial agar plate. To confirm this finding, an enrichment study was done in the belief that any injured bacteria would be able to repair and grow in the enrichment medium and would appear in the agar plate. However, after treatment, total aerobic bacterial count ranged from 0.8 to 1.3 log CFU/ml and no *E. coli* was found in the enrichment study, indicating that the solar disinfection process was able to inactivate coliform, *E. coli* and *E. coli* O157:H7 in water. Furthermore, when 10^6 CFU/ml of *E. coli* was inoculated deliberately into the sari-filtered water and was exposed to sunshine using the solar pasteurization device, similar bactericidal reduction was observed (Table 1). *E. coli* confirmatory tests are shown in Figure 4. This finding suggested that sari filtration of pond/river water followed by exposure to sunlight for 4 hours using the solar pasteurization device could be effective in disinfecting the diarrheal pathogens (Castro-Alférez *et al.* 2017). This might be due to the synergistic effect of solar emission intensity, heat generation and mildly anaerobic conditions occurring inside the polyethylene bags, creating an environment that is destructive for bacteria.

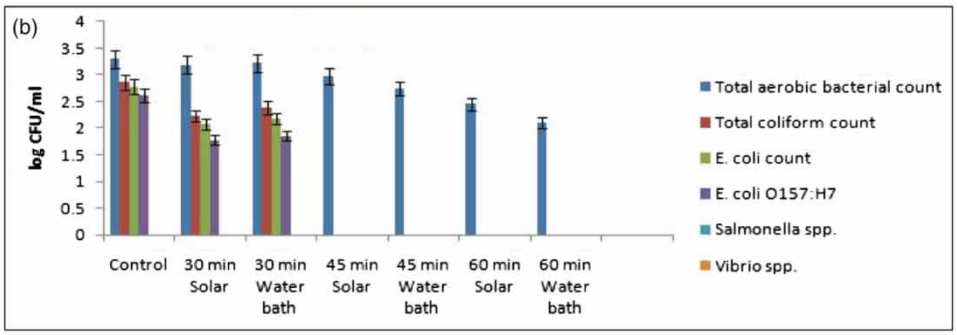
Effect of heat and UV on the bacterial populations

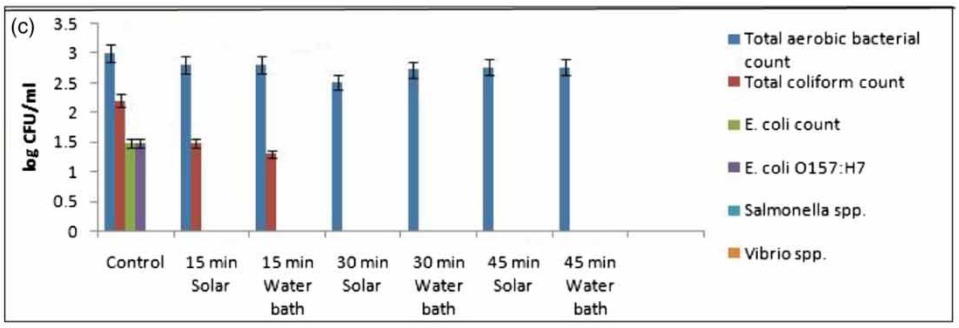
To understand the synergistic effect of heat and UV radiation emissions on the destruction of microorganisms, a temperature controlled water bath and the solar pasteurization device were used and the temperature was set at 45 °C, 50 °C, 55 °C and 60 °C for both devices. The results are presented in Figure 5. It was observed that, irrespective of treatment time, UV radiation emissions had some effect on the diarrheal pathogens at 45 °C, and complete elimination of the diarrheal pathogens were evident in the solar pasteurization device exposure water compared with thermal treatment (Figure 5). On the other hand, irrespective of exposure to sunshine or heat, increasing the temperature up to 55 °C increased the rate of inactivation of diarrheal pathogens with a decreased exposure time. Maximum reduction of aerobic plate count (APC) and elimination of diarrheal pathogens in the solar pasteurization device experiment occurred at 55–60 °C for 30 minutes, compared with the water bath treatment (Figure 5). This result also provides evidence that solar radiation emissions had additional capacity in killing diarrheal pathogens than that of thermal treatment alone (Ellis 1991). This bacterial reduction might be due to the synergistic effect of (1) prolonged UV radiation emissions, (2) increased temperature generated heat, and (3) transformation of the internal environment to mildly anaerobic. Furthermore, the treatment might inactivate bacteria by cell lysis and endotoxins may be released into the treated water that may cause toxicity to the consumers. To confirm this hypothesis, a bacterial endotoxin test was done and the results revealed that no endotoxin (measured in endotoxin units, EU) was released (at 0.125 EU/ml of sensitivity) by cell lysis in the treated water (Figure 6).

Effect of heat and UV on the quality of stored water

The microbiological and physicochemical analysis results showed that the solar pasteurization device-treated water could be stored for 6 months at room temperature. Non-







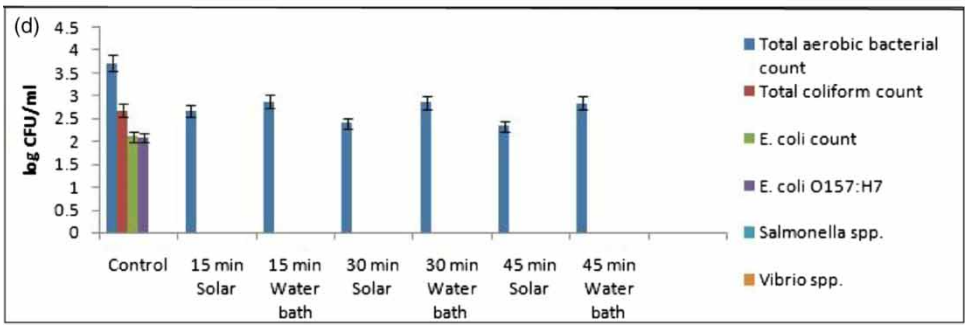


Figure 5 | Effect of temperature on the bacterial destruction in water exposed to sunshine and the comparison of bacterial quality of water in the pasteurization device exposed to sunshine and in the water bath. (a) 45 °C, (b) 50 °C, (c) 55 °C, (d) 60 °C (detection limit <1 log CFU/ml).

significant differences in physicochemical and microbiological parameters (below detection limit) were observed throughout the study (Table 3). These findings also suggested that this device could be used at the household level or for emergencies.

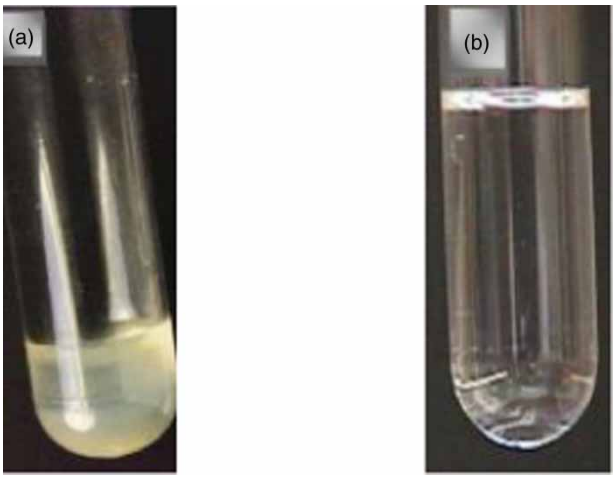


Figure 6 | (a) Positive control (*E. coli* O111:B4) result showing the gel clot after adding the LAL reagent and incubation; (b) negative result of test sample showing no gel formation (at 0.125 EU/ml of sensitivity) after addition of LAL reagent and incubation.

DISCUSSION

In order to improve access to potable water, a low-cost, simple technology was sought for providing safe drinking water to rural households of Bangladesh. While developing the technology, a group of researchers at the University of Dhaka has developed a low-cost domestic device to remove diarrheal pathogens from surface water using free solar energy (Rabbani 2002). This study, simplified the previous device and evaluated the effectiveness of the simplified device in inactivating the diarrheal pathogens present in pond/river water.

The inactivation effect of sunlight on microorganisms has been known for 4,000 years (Castro-Alférez *et al.* 2016). The solar insolation that reaches the Earth's surface is very broad covering radiation wavelengths of generally 300 nm and upwards. Studies have shown that inactivation of microorganisms is achieved by the combined action of mild heat and UV photons over microorganisms, especially UV-A and UV-B (Bichara *et al.* 2011; Petkar *et al.* 2013; Zhang *et al.* 2015). In contrast, several important factors may alter the efficiency of solar disinfection, including solar irradiation emissions intensity and energy dose, water temperature during treatment, water turbidity, dissolved oxygen and dissolved organic matter in the contaminated water, and nature of the microorganisms (Castro-Alférez *et al.* 2016).

On a typical, clear, sunny day in Bangladesh (during February to July), when the solar radiation is strong, this simple device was able to disinfect (pasteurize) three batches of water (about 15 litres of drinking water) in a day. However, during the winter season (December to February), when the solar radiation is less strong, 5–10 L could be obtained per day. So, this device is most dependent on the intensity of sunshine. On a sunny day, the sunlight intensity is high, and thus water will be heated faster to reach >60 °C, required for pasteurization. In contrast, on a cloudy day, water temperature might not reach >60 °C, but UV radiation emissions could still destroy the diarrheal pathogens at 50 °C (Rabbani 2002). Two most significant factors were observed in reaching these high temperatures: (1) the heat gained from the solar radiation and (2) the heat lost to the surroundings. The first should be as high as possible and the second should be as low as possible. Since insulation at the bottom and the air gap between the top transparent sheets are important to preserve heat energy, these must be maintained with due care. Solar radiation is the general source of heat, and necessary to achieve adequate water treatment, but if the device lacks insulation, a considerable amount of heat loss may occur and the temperature will not increase as desired. Greater thickness of insulation at the bottom and a double air gap reduces heat loss.

The most difficult task faced while performing the solar radiation emissions test was the maintenance of identical initial temperature for all tests, since the outdoor temperature was not as constant as the indoor temperature. The sample preparation time before starting the tests varied slightly each time, which affected the initial water temperature. In addition to the variation of time for preparation, the initial device temperature also varied in obtaining the solar radiation. These might affect the results slightly; however, the most important factor is that uninterrupted sunshine is available for at least 2 hours to inactivate the pathogens in water and make it safe to drink. In addition, prevalence of enteropathogenic *E. coli* O157:H7 was observed in pond and lake water samples, indicating recent sewage or animal waste contamination (Table 1). Olsen *et al.* (2002) demonstrated a cohort study among people consuming water from an Alpine municipal water supply; microbiological analysis of participants' stool samples revealed that they were nine times more likely to become ill than those who did not drink that water, which was recently contaminated.

Thus, by considering the microbiological, physicochemical and storage study, this low cost, simple process could be used for converting pond/lake/river water to potable water, in water-scarce areas of the world. Furthermore, the materials required to prepare the pasteurization device are readily available throughout the world.

CONCLUDING REMARKS

The cost of the solar water pasteurization device was approximately 400 BDT (≈US$5). In addition, the device consists of a bamboo tray, black paint, straw, polyethylene sheets and polyethylene bags, which are readily available in rural areas. These devices can be used for daily household needs as well as during emergencies. If proper training is provided to rural people before floods or any emergency and the required materials are supplied, the people will be able to use this device on rafts or at emergency shelters during floods.

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