

Effectiveness of solar disinfection (SODIS) in rural coastal Bangladesh

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ABSTRACT

Scarcity of drinking water in the coastal area of Bangladesh compels the inhabitants to be highly dependent on alternative water supply options like rainwater harvesting system (RWHS), pond sand filter (PSF), and rain-feed ponds. Susceptibility of these alternative water supply options to microbial contamination demands a low-cost water treatment technology. This study evaluates the effectiveness of solar disinfection (SODIS) to treat drinking water from available sources in the southwest coastal area of Bangladesh. A total of 50 households from Dacope upazila in Khulna district were selected to investigate the performance of SODIS. Data were collected in two rounds to examine fecal coliform (FC) and *Escherichia coli* (*E. coli*) contamination of drinking water at the household water storage containers and SODIS bottles, and thereby determined the effectiveness of SODIS in reducing fecal contamination. All water samples were analyzed for pH, electrical conductivity, turbidity and salinity. SODIS significantly reduced FC and *E. coli* contamination under household conditions. The median health risk reduction by SODIS was more than 96 and 90% for pond and RWHS, respectively. Besides, turbidity of the treated water was found to be less than 5 NTU, except pond water. Only 34% of the participating households routinely adopted SODIS during the study.

Key words | coastal Bangladesh, drinking water, fecal contamination, solar disinfection

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INTRODUCTION

Access to safe drinking water is a basic need for humans. Unsafe drinking water along with poor sanitation and hygiene are the main contributors to an estimated 4 billion cases (attributes to 88%) of diarrheal diseases annually, causing 1.8 million deaths, mostly children below 5 years of age (WHO 2005). Unfortunately, almost 84% of the world's population who inhabit rural areas are currently using unimproved sources of drinking water, viz., surface water, unprotected spring and well water, and water from tanker trucks, etc. (WHO & UNICEF 2008). To overcome the challenge of providing safe drinking water to the rural poor in developing countries, point of use (POU) water treatment is being extensively promoted (WHO 2007; Sobsey *et al.* 2008; Hunter 2009; Meierhofer & Landolt 2009). However, the prime challenges in disseminating such

technologies are dependent on performance efficacy and sustained use (Sobsey *et al.* 2008).

Sobsey *et al.* (2008) documented a variety of POU technologies that basically work through either a process of disinfection (chlorination with safe storage, combined coagulant, and solar disinfection) or filtration (ceramic filter and bio sand filter). Solar water disinfection (SODIS) is a low-cost technology with a high efficacy in eliminating waterborne pathogens and reducing diarrheal diseases (Rainey & Harding 2005a, b; Amin & Han 2009; Mäusezahl *et al.* 2009; Meierhofer & Landolt 2009; du Preez *et al.* 2010; Lewis *et al.* 2011; McGuigan *et al.* 2012). More than 5 million people spread over more than 50 countries in Asia, Latin America and Africa use this method (McGuigan *et al.* 2012). However, the main obstacle

in effective implementation of SODIS is it demands some behavioral changes for the user, such as to prepare bottles by cleaning and fill them with water and put them in the sun and collect them afterwards, cleaning the glass used for drinking before consumption of water (Rufener *et al.* 2010; McGuigan *et al.* 2012). Moreover, the effectiveness of this technology in reducing diarrheal disease risk will be hindered if used intermittently, not used for long periods, treated some of the water of daily use, or provided to only some of the household members (Hunter 2009). Although a higher compliance rate is observed during study, this may drop profoundly in post-study (Rainey & Harding 2005a; Rose *et al.* 2006; Sobsey *et al.* 2008).

In Bangladesh, 73% of the population live in rural areas that uses tubewell water as the primary source of drinking water (WHO & UNICEF 2010). These tubewells are installed at various depths depending on the availability and the level of groundwater. However, it is difficult to find a dependable water supply system in the coastal area of Bangladesh because fresh water aquifers are unavailable at a reasonable depth (Kamruzzaman & Ahmed 2006; Islam *et al.* 2010). Besides, many places in the coastal districts are not suitable for even deep tubewells because of the high salinity in groundwater. As a result, harvesting rainwater becomes the only source of drinking water for the inhabitants of these areas and they preserve rainwater in natural or man-made ponds (Kamruzzaman & Ahmed 2006; Alam *et al.* 2011). Therefore, an alternative water supply option such as pond sand filter (PSF), rainwater harvesting system (RWHS) and rain-feed ponds became the main source of drinking water supply for the coastal population of Bangladesh.

Delivery of safe drinking water continues to be a significant priority in the coastal area of Bangladesh because of higher incidence and prevalence of waterborne diseases. People living here drink water mostly from PSF, RWHS or rain-feed pond without any in-house treatment. Several recent studies (Ahmed *et al.* 2005; Karim 2010; Islam *et al.* 2011) showed that water from PSF, RWHS and rain-feed pond are microbiologically contaminated and not safe. The fecal coliform (FC) counts in water from PSF were found to vary from nil to over 4,000 cfu/100 mL (Kamruzzaman & Ahmed 2006; Islam *et al.* 2011). Some studies (Howard *et al.* 2006; Karim 2010; Islam *et al.* 2011) in

Bangladesh showed that the rooftop harvested rainwater satisfies the national and WHO physical and chemical water quality standard, although microbiological contamination was found to occur to a great extent. This indicates the need for a proper treatment technology to use rainwater for drinking. Besides, rain-feed pond waters become dangerously polluted due to unhygienic sanitation, indiscriminate uses and non-protection. Here, the FC and *Escherichia coli* counts were found to vary from 12 to 10,000 cfu/100 mL and from nil to 3,000 cfu/100 mL, respectively (Islam *et al.* 2011) along with several pathogenic bacteria. Therefore, household-based water quality intervention, such as SODIS, may be used to reduce microbial contamination to provide safe drinking water. However, the effectiveness of SODIS in reducing microbial indicators under realistic household use conditions has not been previously investigated in the coastal area of Bangladesh. This study aims to evaluate the effectiveness of SODIS to remove microbial contamination and the acceptability of this technology in rural coastal Bangladesh.

METHODOLOGY

Study area

We considered Dacope upazila in the Khulna district as the study area (Figure 1). It is one of the coastal districts of Bangladesh and is severely affected by salinity. Even deep tubewells are not useful here because deep aquifers are also affected by salinity. Consequently, there is a scarcity of safe drinking water and most of the communities are dependent on multiple sources for drinking water. These were the primary selection criteria for the study area.

Experimental design

A reconnaissance survey was conducted in the study area before household selection. During the reconnaissance survey we chose two households randomly from each of the seven villages selected for the study and interviewed them to collect information regarding their drinking water sources, water collection and treatment method. Discussions were also held with the officials of the Department of Public

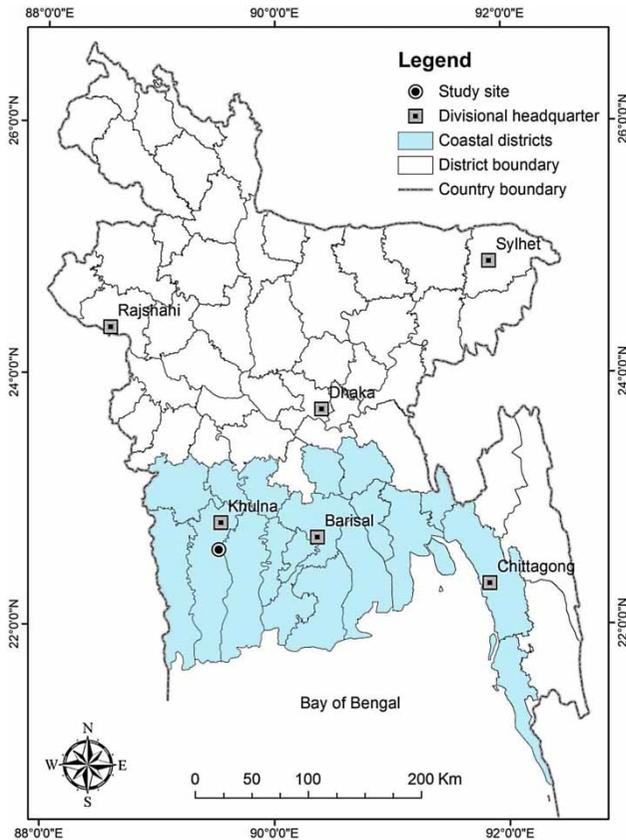


Figure 1 | Map of Bangladesh showing the study area.

Health and Engineering (DPHE) and non-governmental organizations (NGOs) regarding the existing water supply system. After the reconnaissance survey we conducted a field visit for household selection and baseline data collection. A total of 50 households were selected from seven villages of the study area by systematic random sampling. In selecting the households we took every 10th household starting from any side of the village. In case of any household refusing to participate, we considered the nearest one. Since the female-head of every household is primarily associated with collection and treatment of drinking water (WHO & UNICEF 2010), hence only the female-head from each of the selected households was interviewed and trained to apply SODIS. The respondents were questioned regarding water supply, water treatment, sanitation, and hygiene behavior. The effectiveness of the SODIS method was assessed by laboratory analysis of water samples collected from the trained households.

For each of the selected households we provided in-house training on the application of SODIS. The training

sessions were conducted by enumerators who were also well trained about the aspects of community work and data collection. The participants received information about: the sources of water pollution, the ways of contamination of water, health risks of consuming contaminated water, and implementation of SODIS method for drinking water. They were instructed to fill PET bottles and place it in direct sunlight for a minimum of 6 hours. However, to reduce the burden of maintaining time, they were instructed to place the bottle outdoors from early morning to the end of the day. In addition, a poster containing a detailed pictorial demonstration of the SODIS method was fixed at a suitable place in each of the households, so that they can recall the process. Since it is recommended for SODIS to be consumed within 48 hours of treatment (McGuigan *et al.* 2012), participants were instructed to store the water for not more than 48 hours. All the participating households were provided with two clear PET bottles (each of 2 L capacity) for every person in the household for a period of 2 months. This allowed the rotation of two sets of bottles so that half of the set of bottles were exposed on day 1 and consumed on day 2 while the second set was being exposed on day 2 and consumed on day 3 in an ongoing cycle. The average daily water consumption in the study area is about 3.35 L/d (Islam *et al.* 2013). Although, the number of bottles provided per person may not supply the daily drinking water demand of the households, the objective was to encourage them to apply SODIS and gradually adopt the method.

To evaluate the performance of SODIS, water sampling was carried out in two rounds consecutively in April and May 2013. It was dry season and the reason behind sampling at this time was two-fold: (i) abundance of high sunlight and (ii) higher dependence on pond water for drinking purposes. In each of the rounds, water samples from all the households were collected in a single visit. In addition, in each of the sampling rounds, enumerators visited a subset of the participating households over the course of the following 2 months for short spot checks to objectively verify the usage of the method and to sample water for bacteriological analysis. Here, each of the subsets represented 50% of the selected households. Households not using the method at the day of sampling were excluded. None of the households were found to use PSF water during the

sampling time. After 2 months of the study we conducted a post-survey to assess the intervention use and preference of the SODIS method.

Water quality analysis

We examined FC and *E. coli* contamination of drinking water in the first round and FC contamination in the second round of analysis. Water samples were collected from household water storage containers and SODIS bottles to determine the effectiveness of SODIS in reducing levels of fecal contamination from household containers. Water samples were collected following the standard procedures (APHA 1998). For microbiological analysis, 500-mL water samples were aseptically collected in sterile Nalgene plastic bottles. All samples were placed in an insulated box filled with ice packs (Johnny Plastic Ice; Pelton Shepherd, Stockton, CA, USA) and transported to the Environmental Microbiology Laboratory of the Environmental Science Discipline, Khulna University for bacteriological analysis immediately after collection. We assessed the concentration of FC and *E. coli* using the membrane filtration technique. For enumeration of FC and *E. coli*, 100-mL of water samples were filtered through a 0.45 µm pore-size membrane filter (Millipore Corp., Bedford, MA, USA), and the filters were placed on mFC and mTEC agar plates, respectively, following standard procedures (APHA 1998; Islam *et al.* 2007). The mFC plates were incubated at 44 °C for 18–24 hours for enumeration of FC, and mTEC agar plates were incubated at 35 ± 0.5 °C for 2 hours followed by further incubation at 44.5 ± 0.2 °C for 22–24 hours for enumeration of *E. coli*. After incubation, characteristic blue colored colonies were counted as FC and red or magenta colored colonies were counted as *E. coli* and expressed as colony forming units (cfu) per 100 mL. All water samples were analyzed for pH, electrical conductivity (EC), turbidity and salinity. Physico-chemical analyses were performed according to APHA (1998).

Health risk assessment

A quantitative health risk assessment (QHRA) model was used to quantify the likely disease risk associated with the water supply options. QHRA is a simple deterministic spreadsheet model developed by the Arsenic Policy Support Unit of

the Government of Bangladesh. The model estimates microbial disability-adjusted life years (DALYs) for three reference pathogens, rotavirus, cryptosporidium and *E. coli* for viral, protozoal and bacterial diseases, respectively, to determine the total disease risk. The output of the model is expressed as µDALY/person-yr, which is a globally accepted parameter to measure health risk. The details of the model assumptions regarding pathogen and indicator organisms and the dose-response relationship are beyond the scope of this paper, but can be found in other literature (Ahmed *et al.* 2005; Howard *et al.* 2006, 2007). The *E. coli* data were used to estimate the likely disease risk associated with each water supply option in DALYs, a globally applied matrix as recommended by WHO (2004) to compare different disorders and diseases with different health outcomes.

Data analysis

Statistical analysis was performed by SPSS V.16 statistical software. Since the data failed to meet the assumption of normal distribution, hence parametric tests cannot be used to compare samples. Therefore, non-parametric tests were used, which work with ranks rather than absolute numbers. Medians, averages and ranges were used for descriptive purposes. The Mann–Whitney *U* test was employed to analyze the differences in bacterial concentrations between storage water and SODIS treated water.

RESULTS

Characteristics of the participants

Table 1 shows characteristics of the participants. The age of the participants varied between 15 and 57 years. Around 20% of the participants were illiterate and 40% passed secondary level. About 65% of the households had a family size of between 3 and 5 members. Approximately 58% of the participants reported their annual family income to be between 36,000 and 60,000 BDT (Bangladeshi taka). The majority of the participants (74%) use alum (locally known as *phitkari*) for water treatment, and about 24% of them do not use any in-house treatment for drinking water.

Source wise performance of SODIS

Table 2 shows range, mean and median values for FC and *E. coli* concentrations in the water of household storage containers and of SODIS bottles, with respect to the sources (both rain-feed pond and RWHS) of water. The household storage water of both ponds and RWHSs showed higher indicator bacterial contamination compared with SODIS treated pond and RWHS water. Median FC concentration of water from household storage containers for rain-feed pond and for RWHS were 900 cfu/100 mL and 270 cfu/100 mL, respectively, in the first round of water sample analysis. However, after SODIS treatment, the concentrations were found to be 13.5 cfu/100 mL and 26 cfu/100 mL, respectively. Maximum indicator bacterial concentrations of pond water were very high compared with RWHSs.

Table 2 also shows the efficiency of SODIS in removing indicator bacteria. FC and *E. coli* concentrations reduced significantly in both rain-feed pond and RWHS water samples in the first round of sampling ($p < 0.05$). Here, the overall reductions of *E. coli* were respectively 89.7% and 95% and for FC were, respectively, 96.1% and 98.2% for pond water and RWHS. Again, in the water samples of the second round of sampling, FC concentrations reduced significantly by 99.7% and 74.6% for both pond and RWHS water, respectively.

Figure 2 shows the comparison of *E. coli* contamination of water from pond water storage containers with SODIS bottles among the study households. About 74% of the storage container samples were contaminated by *E. coli* compared to 32% of the SODIS bottle samples; 24% of the stored samples showed higher health risk (*E. coli* ≥ 100 cfu/100 mL of water) compared to 11% of the SODIS samples.

Physico-chemical quality of water sources

A summary of the physico-chemical parameters of the water samples is shown in Table 3. The pH value of most of the water samples remained within the Bangladesh drinking water quality standard (BDS) and WHO guideline values of 6.5–8.5. In the second round of analysis, only two of the RWHS samples were found to have a pH value of more than 8.5. For pond water, higher EC was observed which indicates a higher amount of dissolved substances in the

Table 1 | Characteristics of the participants ($n = 50$)

Socio-demographic factors	Percentage (%)
Age	
< 30 years	20
30–40 years	40
> 40 years	40
Years of schooling	
Illiterate	20
Primary (up to 5)	25
Secondary (up to 10)	40
Passed SSC/HSC/Bachelor/Masters	15
Job	
Small business	25
Farmer	45
Day laborer	15
Others	15
Family size (family members)	
3–5	65
6–10	30
> 10	5
Annual income (BDT)	
36,000–60,000	57.5
> 60,000–84,000	25
> 84,000	17.5
In-house practice of water treatment	
Alum	74
Solar disinfection	2
None	24
Water stored in covered container	70

BDT, Bangladeshi taka; 1USD = approximately 78 BDT.

water. Except for a few pond water samples, the turbidity of all treated water samples was well below the BDS acceptable value of 5 NTU. However, the turbidity of pond water was reduced significantly by applying SODIS. Here, the average removal of turbidity was more than 53% and 61%, respectively, in the first and second round of analysis.

Health risk assessment

Application of SODIS reduces the health risk associated with both the rain-feed pond and RWHS, as shown in

Table 2 | Source-wise microbial counts (in cfu/100 mL) and microbial reduction by SODIS treatment

Sampling	Source water and parameter	Storage water			SODIS water			Ave % reduction	
		Range	Mean	Median	Range	Mean	Median		
First round	Rain-feed pond water ($n = 39$)	FC	0–10,000	1,922	900	0–100	25.27	13.5	96.1
		<i>E. coli</i>	0–1,000	58.84	20	0–100	17.51	0	89.7
	RWHS ($n = 3$)	FC	0–500	271.3	270	0–44	8.66	26	98.2
		<i>E. coli</i>	0–100	35.66	6	0–10	3.33	0	95
Second round	Rain-feed pond water ($n = 3$)	FC	1,900–4,300	2,867	2,400	0–17	9	11	99.71
	RWHS ($n = 25$)	FC	0–200	44	24	0–32	9	8	74.6

RWHS, rainwater harvesting system; in the first and second round of the sampling, the number of water samples collected from both household storage container and SODIS bottles for rain-feed pond water and RWHS were 39, 3 and 3, 25, respectively.

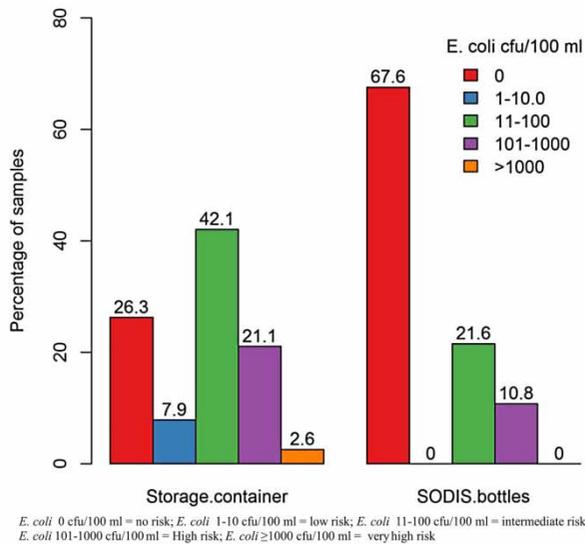
**Figure 2** | Comparison of *E. coli* contamination of water from household storage container for rain-feed pond water with SODIS treated water.

Figure 3. As shown, viral and bacterial pathogen concentrations dominated the disease risk, but the protozoal risk was relatively negligible. At the lower estimation (5th percentile), the viral disease risk was the most significant contributor for stored pond and RWHS water. However, after applying SODIS, the disease risk reduced to almost nil. As shown in **Figure 3**, the median disease risk of treated pond and RWHS water was significantly low. The median health risk reduction was about 96% and 90% for pond and RWHS water, respectively. However, at higher disease risk estimation (95th percentile), an insignificant health risk reduction by SODIS was observed and both viral and bacterial disease risks were dominant.

Social preference of SODIS

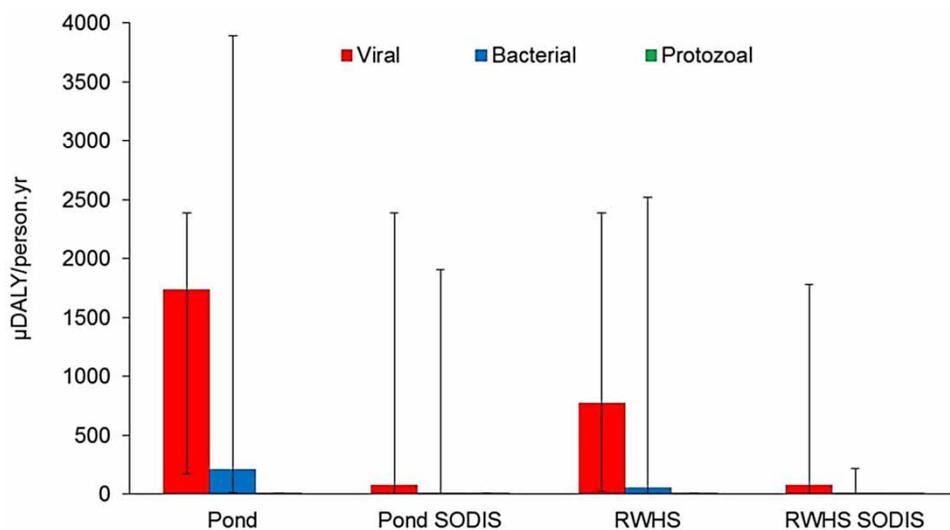
To assess the social preference and adaptation of SODIS, we conducted a post-survey among the selected households after 2 months of the study and we found only 4% of the participants had been using SODIS. However, during the study period about 34% used SODIS regularly, 36% used it for 4 days in a week, 18% used it 3 days in a week, and the remainder were more irregular (**Table 4**). The respondents who were irregular in using SODIS were asked to identify the reasons for not using it and they reported several reasons, viz., reluctant about treatment (50%), difficult to treat the large amount of water required (39%) and difficult to manage time for the treatment process (11%). All of the respondents agreed that SODIS is easy to apply and almost all of them (98%) reported that drinking water from SODIS bottles can reduce diarrhea. However, only 52% of them thought SODIS would be socially acceptable and 60% believed it was cheap. Among the respondents who thought SODIS would be socially unacceptable (48%), 12% of them believed that SODIS is expensive, while 36% said it is difficult to treat the large amounts of water required for family members. Only 22% of the respondents agreed to buy bottles for SODIS.

DISCUSSION

The research was conducted under daily household use condition in the study area which represents varied water quality and hygiene practices. Results indicate that SODIS can reduce the indicator bacterial levels of the water

Table 3 | Physical and chemical water quality of the storage and SODIS treated water samples

Sampling	Option	Parameter	Storage water		SODIS water		Ave % reduction
			Range	Mean	Range	Mean	
First round	Rain-feed pond water (<i>n</i> = 39)	pH	4.50–8.56	7.39	4.78–8.08	7.43	–
		EC(μ S/cm)	773–5,630	2,649	341–5,390	2,563	–
		Salinity (ppt)	0.38–2.85	1.33	0.67–2.22	1.29	–
		Turbidity (NTU)	0.72–99.10	12.17	0.50–63.50	5.8	53
	RWHS (<i>n</i> = 3)	pH	7.52–7.69	7.60	7.60–7.74	7.67	–
		EC(μ S/cm)	123–188	151	115–160	141	–
		Salinity (ppt)	0.05–0.08	0.06	0.04–0.07	0.05	–
Second round	Rain-feed pond water (<i>n</i> = 3)	pH	7.2–7.4	7.3	7.3–7.8	7.46	–
		EC(μ S/cm)	1,219–1,603	1,374	1,246–1,572	1,362	–
		Salinity (ppt)	0.61–0.80	0.68	0.62–0.79	0.68	–
		Turbidity (NTU)	2.15–15.7	7.6	1.31–3.85	2.25	61%
	RWHS (<i>n</i> = 25)	pH	6.70–9.60	7.21	6.80–8.90	7.47	–
		EC(μ S/cm)	27–1,549	147	15–156	70	–
		Salinity (ppt)	0–0.78	0.05	0–0.06	0.02	–
		Turbidity (NTU)	0.81–20	2.64	0.67–4.20	1.88	–

**Figure 3** | Health risks of the water sources before and after SODIS treatment. The bar represents the median health risks, and the upper and lower bound of the middle line in the bars represent the upper (95th percentile) and lower (5th percentile) health risks, respectively.

supply options significantly, although the performance of SODIS did not meet the WHO protective level (WHO 2011). Previous studies (Rainey & Harding 2005b; du Preez *et al.* 2011) also designate that SODIS can reduce indicator bacterial contamination significantly under daily household use conditions.

Water supply options evaluated in this study indicate a significantly higher disease risk compared to the

recommended disease risk of 1×10^{-3} DALYs/1000 person-yr (WHO 2004). The disease risk was primarily dominated by bacterial and viral pathogens. As indicated by this study, the median health risk was found to significantly reduce by the introduction of SODIS at the household level. Although a significant microbial health risk reduction was observed, intervention at the household level by the SODIS alone cannot ensure complete microbial safety of drinking water.

Table 4 | Responses of participants about the preference of water treatment options

	Yes (%)	No (%)
Do you think SODIS can purify water?	98	2
Did you use SODIS regularly during the study period?	34	66
Do you think drinking water from SODIS bottles can reduce diarrhea?	98	2
Did you experience less waterborne disease by drinking SODIS water?	80	20
Do you think SODIS is expensive?	40	60
Do you think use of SODIS will be socially acceptable?	52	48
Do you think use of SODIS is difficult?	0	100
Do you know where you will get SODIS bottle?	84	16
Will you buy bottle for SODIS?	22	78
Are you using SODIS now?	04	96

In the first round of analysis, there were three SODIS samples where the level of contamination increased compared to the respective control samples; it is possible only if the bottles were not exposed to sunlight, or kept in a place where sunlight was not abundant at the required level, or recontamination occurred due to improper handling. This raises the important issues of correct placement of SODIS bottles to ensure maximum exposure to ultraviolet rays and proper handling of the bottles to avoid recontamination. The motivation to adhere to the protocols in a sustainable way set for water quality interventions is greatly influenced by human behavior and has been problematic in previous SODIS studies (Mäusezahl *et al.* 2009; Rai *et al.* 2010). In the second round of analysis, only two RWHS samples were found to have a pH value of more than 8.5. These were the harvested rainwater samples collected from a reinforced cement concrete (RCC) tank. The pH value of stored rainwater in an RCC tank is normally found to be higher than the recommended maximum value due to leaching of calcium-oxide from the cement used for construction of the tank (Karim 2010). As turbidity of the SODIS treated pond water reduces, the water becomes very clear and transparent, which is more aesthetically acceptable for drinking. It is necessary to mention that using alum for rain-feed pond water is a common practice in the study area and most of the households use alum in the household storage containers, which leads to a good

decrease in turbidity, however, it did not affect the results of this study because rain-feed pond water used for SODIS was collected from the household storage containers and water samples were collected from both the household storage containers and the SODIS treated water.

We communicated SODIS methods and health risk messages to rural women, who conventionally had limited access to information. According to Solvic (1999), men tend to judge risk as being less problematic than women. In addition, women are more health conscious than men with respect to consumptive health behavior (Severtson *et al.* 2006; Burger *et al.* 2008). Therefore, the technique used to disseminate information in this study not only has the potential to reduce gender inequality in water consumption knowledge, but can also reduce the consumption of contaminated water since water collection and treatment for drinking purposes is generally done by the woman-head of the household. Thus, by communicating the SODIS method to women, we reached the target audiences because they can play a vital role in changing the consumption behavior of the household members.

In this study, only 34% of the selected households used SODIS regularly, which indicates a lack of consciousness regarding safe drinking water. To reduce the health risk associated with consumption of contaminated water it is necessary to inform coastal communities about possible risks from different drinking water sources besides introducing methods that can minimize these risks. Providing risk messages is not expected to be a magic bullet, but proper risk messages will make people aware of their own risk which will lead to positive behavioral changes. Studies (Caldwell *et al.* 2003; Burger 2004; Keraita *et al.* 2008) have also shown that knowledge does not always necessarily transmit into practice; however, it is generally assumed that knowledge of risk encourages people to take precautions to reduce such risk (Brewer *et al.* 2004). In the dry season (November–May), the households mainly drink rain-feed pond water because rainwater is rarely available in the rainwater tanks. Conversely, in the wet season (June–October), they depend on harvested rainwater. This may have been the reason why only 4% of the selected households used SODIS during the post-survey as it was conducted in the wet season. However, during the second round of sampling, we found the majority of the households using rainwater due

to early rainfall. Therefore, it is presumable that the SODIS method communicated with a proper risk message may lead to an increased use of SODIS for pond water, especially in the dry season.

During the questionnaire survey only a few participants reported that they will buy PET bottles for SODIS, whereas approximately half of the respondents thought that SODIS may not be socially acceptable. Therefore, changes in consumption behavior are partly dependent on a proper awareness program and availability of PET bottles within short distances of the households. It was also observed that the households were not properly cleaning the storage container and were collecting the water from the container in an unhygienic way, such as dipping dirty hands in it. Thus, the storage container becomes a reservoir for microbial growth. Therefore, safe in-house water storage and good hygienic practices are important issues that need to be addressed by a water safety plan (WSP) for long-term sustainability of SODIS in delivering safe water to the users.

CONCLUSIONS

It is obvious from the data presented in this study and in previous studies that the water supply options currently used in the southwest coastal areas of Bangladesh pose a significant health risk. Rain-feed pond water has higher health risks compared with other options. The study findings showed that water treatment using SODIS can remove microbial contamination of the household storage water significantly. Although a significant microbial removal and health risk reduction was observed, intervention by SODIS alone cannot ensure complete microbial safety of drinking water. About 34% of the households in the study adopted SODIS on a routine basis during the study period, whereas others used it either intermittently or only when they had time. Despite the fact that the SODIS method was not widely adopted, the experience from this study indicates the future efforts to improve water quality and reduce diarrhea in the coastal areas of Bangladesh. Proper education and training of the rural community about the sources of water contamination, health risks of consuming contaminated drinking water, and benefits and barriers of SODIS should be conducted. Good hygienic practices and WSPs should

be implemented for all water supply options to ensure the supply of safe drinking water in the long term. The use of WSPs should also support greater community participation because of its emphasis on working with communities to monitor and manage their water safety effectively.

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REFERENCES

- Ahmed, M. F., Shamsuddin, S. A. J., Mahmud, S. G., Rashid, H., Deere, D. & Howard, G. 2005 *Risk Assessment of Arsenic Mitigation Options (RAMMO)*. APSU, Dhaka, Bangladesh.
- Alam, A., Rahman, M. & Islam, S. 2011 *Performance of modified design pond sand filters*. *J. Water Supply Res. Technol. AQUA* **60** (5), 311–318.
- Amin, M. T. & Han, M. Y. 2009 *Roof-harvested rainwater for potable purposes: application of solar collector disinfection (SOCO-DIS)*. *Water Res.* **43** (20), 5225–5235.
- APHA (American Public Health Association) 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edn. American Public Health Association, Washington, DC.
- Brewer, N. T., Weinstein, N. D., Cuite, C. L. & Herrington Jr, J. E. 2004 Risk perceptions and their relation to risk behavior. *Ann. Behav. Med.* **27** (2), 125–130.
- Burger, J. 2004 *Fish consumption advisories: knowledge, compliance and why people fish in an urban estuary*. *J. Risk Res.* **7** (5), 463–479.
- Burger, J., Shukla, S., Fitzgerald, M., Flores, S. & Chess, C. 2008 *Fish consumption: efficacy among fishermen of a brochure developed for pregnant women*. *J. Risk Res.* **11** (7), 891–904.
- Caldwell, B. K., Caldwell, J. C., Mitra, S. N. & Smith, W. 2003 *Tubewells and arsenic in Bangladesh: challenging a public health success story*. *Int. J. Popul. Geogr.* **9** (1), 23–38.
- du Preez, M., Conroy, R. M., Ligondo, S., Hennessy, J., Elmore-Meegan, M., Soita, A. & McGuigan, G. 2011 *Randomized intervention study of solar disinfection of drinking water in the prevention of dysentery in Kenyan children aged under 5 years*. *Environ. Sci. Technol.* **45** (21), 9315–9323.
- du Preez, M., McGuigan, K. G. & Conroy, R. M. 2010 *Solar disinfection of drinking water (SODIS) in the prevention of dysentery in South African children aged under 5 years: the*

- role of participant motivation. *Environ. Sci. Technol.* **44** (22), 8744–8749.
- Howard, G., Ahmed, M. F., Shamsuddin, A. F., Mahmud, S. G. & Deere, D. 2006 Risk assessment of arsenic mitigation options in Bangladesh. *J. Health Popul. Nutr.* **24** (3), 346–355.
- Howard, G., Ahmed, M. F., Teunis, P., Mahmud, S. G., Davison, A. & Deere, D. 2007 Disease burden estimation to support policy decision making and research prioritization for arsenic mitigation. *J. Water Health* **5** (1), 67–80.
- Hunter, P. R. 2009 Household water treatment in developing countries: comparing different intervention types using meta-regression. *Environ. Sci. Technol.* **43** (23), 8991–8997.
- Islam, M. A., Sakakibara, H., Karim, M. R., Sekine, M. & Mahmud, J. H. 2011 Bacterial assessment of alternative drinking water supply options in coastal areas of Bangladesh. *J. Water Health* **9** (2), 415–428.
- Islam, M. A., Sakakibara, H., Karim, M. R. & Sekine, M. 2013 Potable water scarcity: options and issues in the coastal areas of Bangladesh. *J. Water Health* **11** (3), 532–542.
- Islam, M. M., Chou, F. N. -F., Kabir, M. R. & Liaw, C.-H. 2010 Rainwater: a potential alternative source for scarce safe drinking and arsenic contaminated water in Bangladesh. *Water Resour. Manage.* **24** (14), 3987–4008.
- Islam, M. S., Huq, A., Siddika, A., Khan, M. N. H., Goldar, M. M., Sadique, M. A., Kabir, A. N. M. H. & Colwell, R. R. 2001 Microbiological analysis of tube-well water in a rural area of Bangladesh. *Appl. Environ. Microbiol.* **67** (7), 3328–3330.
- Kamruzzaman, A. K. M. & Ahmed, F. 2006 Study of performance of existing pond sand filters in different parts of Bangladesh. *Sustainable development of water resources, water supply and environmental sanitation, 32nd WEDC conference, Colombo, Sri Lanka*, pp. 377–380.
- Karim, M. R. 2010 Microbial contamination and associated health burden of rainwater harvesting in Bangladesh. *Water Sci. Technol.* **61** (8), 2129–2135.
- Keraita, B., Drechsel, P. & Konradsen, F. 2008 Perceptions of farmers on health risks and risk reduction measures in wastewater-irrigated urban vegetable farming in Ghana. *J. Risk Res.* **11** (8), 1047–1061.
- Lewis, M., Pryor, R. & Wilking, L. 2011 Fate and effects of anthropogenic chemicals in mangrove ecosystems: a review. *Environ. Pollut.* **159** (10), 2328–2346.
- Mäusezahl, D., Christen, A., Pacheco, G. D., Tellez, F. A., Iriarte, M., Zapata, M. E., Cevallos, M., Hattendor, F. J., Cattaneo, M. D., Arnold, B., Smith, T. A. & Colford Jr, J. M. 2009 Solar drinking water disinfection (SODIS) to reduce childhood diarrhoea in rural Bolivia: a cluster-randomized, controlled trial. *PLoS Med.* **6** (8), DOI: 10.1371/journal.pmed.1000125.
- McGuigan, K. G., Conroy, R. M., Mosler, H. J., du Preez, M., Ubomba-Jaswa, E. & Fernandez-Ibañez, P. 2012 Solar water disinfection (SODIS): a review from bench-top to roof-top. *J. Hazard. Mat.* **235–236**, 29–46.
- Meierhofer, R. & Landolt, G. 2009 Factors supporting the sustained use of solar water disinfection – experiences from a global promotion and dissemination programme. *Desalination* **248** (1–3), 144–151.
- Rai, B. B., Pal, R., Kar, S. & Tsering, D. C. 2010 Solar disinfection improves drinking water quality to prevent diarrhea in under-five children in Sikkim, India. *J. Global Infect. Dis.* **2** (3), 221–225.
- Rainey, R. C. & Harding, A. K. 2005a Acceptability of solar disinfection of drinking water treatment in Kathmandu Valley, Nepal. *Int. J. Environ. Health Res.* **15** (5), 361–372.
- Rainey, R. C. & Harding, A. K. 2005b Drinking water quality and solar disinfection: effectiveness in peri-urban households in Nepal. *J. Water Health* **3** (3), 239–248.
- Rose, A., Roy, S., Abraham, V., Holmgren, G., George, K., Balraj, V., Abraham, S., Muliylil, J., Joseph, A. & Kang, G. 2006 Solar disinfection of water for diarrhoeal prevention in southern India. *Arch. Dis. Child.* **91** (2), 139–141.
- Rufener, S., Maeusezahl, D., Mosler, H. J. & Weingartner, R. 2010 Drinking water quality between source and point-of-consumption – drinking cups as a high potential recontamination risk: a field study in Bolivia. *J. Health Popul. Nutr.* **28** (1), 34–41.
- Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M. & Elliott, M. A. 2008 Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environ. Sci. Technol.* **42** (12), 4261–4267.
- Svertson, D. J., Baumann, L. C. & Brown, R. L. 2006 Applying a health behavior theory to explore the influence of information and experience on arsenic risk representations, policy beliefs, and protective behavior. *Risk Anal.* **26** (2), 353–368.
- Solvic, P. 1999 Trust, emotion, sex, politics, and science: surveying the risk-assessment battlefield. *Risk Anal.* **19** (4), 689–701.
- WHO 2004 *Guidelines for Drinking-Water Quality*, 3rd edn, Vol. 1, Recommendations. World Health Organization, Geneva.
- WHO 2005 *Progress towards the Millennium Development Goals, 1990–2005*. World Health Organization, Geneva.
- WHO 2007 *Combating Waterborne Diseases at the Household Level. The International Network to Promote Household Water Treatment and Safe Storage*. World Health Organization, Geneva.
- WHO 2011 *Evaluating Household Water Treatment Options: Health-based Targets and Microbiological Performance Specifications*. World Health Organization, Geneva, Switzerland.
- WHO & UNICEF 2008 *Progress on Drinking Water and Sanitation: Special Focus on Sanitation*. World Health Organization and United Nations Children’s Fund, Joint Monitoring Program for water supply and sanitation (JMP), World Health Organization, Geneva.
- WHO & UNICEF 2010 *Estimates for the Use of Improved Drinking Water Sources and Improved Sanitation Facilities*. World Health Organization and United Nations Children’s Fund, Joint Monitoring Program for water supply and sanitation (JMP), World Health Organization, Geneva.

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