Efficacy of an appropriate point-of-use water treatment intervention for low-income communities in India utilizing *Moringa oleifera*, sari-cloth filtration and solar UV disinfection

Syed Imran Ali, Morgan MacDonald, J. Jincy, K. Arun Sampath, G. Vinothini, Ligy Philip, Kevin Hall and Kristan Aronson

ABSTRACT

This study investigated the efficacy of a POU water treatment system featuring sari-cloth filtration and/or *Moringa oleifera* coagulation as pre-treatments for solar disinfection (SODIS). Surface water from a peri-urban slum in Chennai, India, was treated and analysed for turbidity, organic content via chemical oxygen demand (COD) and microbiological quality via most probable number (MPN) enumeration of total coliforms. Pre-treatment with both moringa coagulation and sari-cloth filtration significantly improved the turbidity of raw water compared to no pre-treatment controls ($P = 0.0002$). Optimal moringa coagulation did not outperform sari-cloth filtration ($P = 0.06$), but combining optimal moringa coagulation with sari-cloth filtration significantly outperformed either pre-treatment independently with respect to turbidity ($P = 0.016$ and $P = 0.0001$, respectively). The addition of moringa was found to increase COD in treated water, with greater doses of moringa resulting in higher COD levels ($P = 0.04$). Increased organics may have encouraged the re-growth of coliform bacteria that was observed in those jars receiving moringa coagulant such that, with respect to MPN, those jars which were subject to optimal moringa coagulation did not outperform those undergoing sari-cloth filtration alone ($P = 0.41$). Sari-cloth filtration is recommended as a pre-treatment for SODIS whereas moringa is not, as further investigation on the relationship between organics and bacterial re-growth is necessary.

Key words | appropriate technology, *Moringa oleifera*, point-of-use, sari-cloth filtration, SODIS, water treatment

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INTRODUCTION

Throughout the global south, people living in rural areas and peri-urban slums are often forced to rely upon contaminated surface water as their primary drinking water source, resulting in significant burdens of water-related disease. Point-of-use (POU) water treatment technologies have been shown to improve the quality of drinking water at the household level and can achieve rapid health gains amongst marginalized populations (Fewtrell *et al.* 2005). A range of water treatment options is available for applications at both the household and community level (Sobsey 2002). Sustainable options are those that meet local capabilities in terms of materials and resources, encourage local participation and are flexible, adaptable and socio-culturally appropriate (Murphy *et al.* 2009).

Opportunities and challenges with solar disinfection (SODIS)

Solar disinfection (SODIS) is one of the simplest and most cost-effective methods for improving the microbiological quality of drinking water currently available. NGOs and researchers have implemented several SODIS projects to demonstrate its effectiveness in the Indian context – from

doi: 10.2166/washdev.2011.043

rural areas in the north-eastern state of Assam (Gupta 2004), to urban slums in Sikkim (Rai *et al.* 2010), in small towns of the south in Vellore (Rose *et al.* 2006) and in the megalopolises of Mumbai (Fisher *et al.* 2008) and Chennai (Achuthan 2006). SODIS can employ the effects of thermal and ultraviolet (UV) radiation treatment, inactivating up to 99.9% of waterborne pathogens (Wegelin *et al.* 1994; Hijnen *et al.* 2006). However, SODIS may not be as effective against those bacterial species that are spore-forming, which can survive the inactivation process (Boyle *et al.* 2008). By mimicking the thermal effects of the Nairobi sun, Joyce *et al.* (1996) found that *Escherichia coli* levels were reduced by six orders of magnitude following 7 h of exposure. Similarly, Wegelin *et al.* (1994) found that the synergistic effect of water temperature could enhance the efficacy of SODIS by approximately a factor of two, once a threshold of 50 °C had been reached. Photocatalytic disinfection of waterborne pathogens by UV irradiation is also central to the SODIS method. Gómez-Cousoa *et al.* (2009) found the infectivity of *Cryptosporidium parvum* oocysts to be inversely proportional to radiation intensity. Furthermore, Lonnen *et al.* (2005) found that simulated solar exposure at 200 W m^{-2} in the 300–400 nm UV range produced a 4-log reduction in protozoan, fungal and bacterial viability. Field studies have also demonstrated SODIS can significantly reduce the incidence of diarrhoeal disease in children under the age of five (Conroy *et al.* 1999; Rose *et al.* 2006). However, a meta-regression of randomized controlled trials of several household water treatment technologies by Hunter (2009) suggests that SODIS may not be able to sustain health benefits in the field in the long run. As a positive, compliance with SODIS is generally high. In 75% of visits to the field, Rose *et al.* (2006) found that 78% of households in an urban slum in Vellore, India, practised the SODIS method correctly following a safe water intervention. Similarly, high levels of compliance were also observed in rural areas just outside of Vellore by Firth *et al.* (2010).

In comparison to household chlorination – perhaps the most prevalent POU technique for disinfecting drinking water – SODIS can circumvent the formation of potentially carcinogenic disinfection by-products (DBPs) associated with chemical disinfection of natural waters containing organic compounds. Furthermore, reactions between chemical disinfectants and organics may also produce taste and odour compounds that render the water less palatable, limiting uptake (Freeman *et al.* 2005). For these reasons, SODIS is seen as an attractive option for improving the microbiological quality of water at the household level. Water purification by exposure to solar radiation may be well applied amongst extremely impoverished households as a first-line, gap-filling measure.

The penetration of UV radiation, and thus the effectiveness of the SODIS process, is negatively affected by the presence of colour and turbidity in the water to be treated (Gómez-Cousoa *et al.* 2009). For this reason, treatment with SODIS is not recommended for waters with turbidity greater than 30 NTU (SANDEC 2008). Clarifying water prior to SODIS treatment can improve its effectiveness, and for some natural waters, clarification may be a necessary pre-treatment step. The present study investigates two potential pre-treatment methods for SODIS – cotton sari-cloth filtration alone or in combination with *Moringa oleifera*, a natural plant-based coagulant. These methods may be applied in conjunction with SODIS to form a simple, combined POU treatment system for low-income rural and peri-urban households in the Indian subcontinent and elsewhere.

Moringa oleifera: a potential natural coagulant pre-treatment for SODIS

The use of natural plant materials for the clarification of turbid surface waters has a rich history in India, going back to ancient times. The *Sushruta Samhita*, an early Sanskrit ayurvedic medical text, refers to the use of *Strychnos potatorum* seeds for water clarification, a technique that is still used in parts of rural India today (Babu & Chaudhuri 2005). *Moringa oleifera* is a flowering tree found widely in tropical and sub-tropical climates in South Asia and West Africa and, similarly, its desiccated seed powder has also been observed to have coagulant properties that make it useful for water clarification. For this reason, in addition to its nutritional and traditional uses, *M. oleifera* has also been utilized for water clarification purposes for generations in India (Arnoldsson *et al.* 2008).

Laboratory studies show that moringa coagulation can remove up to 90 to 99% of bacterial contamination and up to 96% of influent *E. coli* (Madsen *et al.* 1987; Nkurunziza *et al.* 2009). Oluduro & Aderiye (2007) noted a 97.5%

reduction of coliform bacteria upon treatment with *M. oleifera*, however, the same study also found secondary bacterial growth of *E. coli*, *Salmonella typhi* and *Shigella dysenteriae* at 185, 189 and 198% of their influent concentrations, respectively, 24 hours post-treatment. Re-growth of secondary bacteria in *M. oleifera* treated water has also been observed in other studies (Madsen *et al.* 1987; Wilson & Andrews 2010). Lea (2010) recommends the frequent treatment of smaller volumes of water in order to avoid bacterial re-growth prior to consumption. The effectiveness of moringa coagulation on natural waters in the field is also unclear. A study by Firth *et al.* (2010) in rural Tamil Nadu, India, found that moringa coagulation did not reduce levels of thermotolerant coliforms in stored village water, though it did with *E. coli*-seeded water in the laboratory. The debate over the efficacy of *M. oleifera* in water treatment is ongoing. Growing naturally in many rural areas, *M. oleifera* could be an inexpensive and widely available coagulant for POU water treatment purposes; however, further testing is required with natural surface waters to determine its bacterial removal efficacy and its potential as a pre-treatment for SODIS.

Socio-cultural factors also influence the regional applicability of moringa as a water treatment method in India. While moringa grows widely throughout the country, its use varies between regions. In south India, the young moringa fruit ('drumstick') is widely used in local cuisine, whereas in north India it is not. For water purification purposes, mature seeds are required. In south India, much of the moringa crop is harvested early on for food purposes. Because of this, mature seeds are hard to come by and may be expensive if they are available. In north India, the moringa fruit is not utilized as a food source, allowing the fruit and its seeds to reach maturity. Having few competing uses, moringa seeds are widely available and inexpensive in north India. For this reason, moringa coagulation may be more appropriate for POU safe water applications in north India than it may be in the south (Ali 2010).

Moringa coagulation has previously been assessed as a pre-treatment for chemical disinfection, with recent studies indicating that moringa may not be a desirable option for use in conjunction with the common chlorination agent sodium hypochlorite (Preston *et al.* 2010). For one, moringa introduces natural organic matter to the treated water which itself exerts a chlorine demand, requiring larger doses of hypochlorite and reducing the likelihood that an adequate residual can be maintained. Furthermore, hypochlorite reacts with natural organic matter to form taste and odour compounds and, more troublingly, trihalomethanes (THMs) and other potentially harmful DBPs (Ghebremichael *et al.* 2006). Given this chemistry, moringa coagulation is not a suitable pre-treatment for chemical disinfection; however, it may be an appropriate pre-treatment prior to UV disinfection, as UV irradiation is not known to induce DBP or taste and odour compound formation in the presence of organics.

Sari-cloth filtration: a second potential pre-treatment for SODIS

The present study also examines simple filtration with used cotton sari-cloth as a pre-treatment for SODIS. Cotton sari-cloth is a material that is available in almost every rural and urban household throughout South Asia (Huq *et al.* 2010). It is commonly used to strain collected water in rural areas. Though sari-cloth is specific to the South Asia region, the filtration effect is likely observable for any previously used cotton fabric. Huq *et al.* (1996) showed that simple cotton sari-cloth, folded several times, produced a filter of effective pore size of 20 μm that had the ability to remove copepod zooplankton, upon which *Vibrio cholerae* are commensal. Colwell *et al.* (2003) then showed that practising this method of filtration yielded a 48% reduction in the incidence of cholera in rural Bangladeshi villages during seasonal epidemics. Though this pore size would be unable to remove free-floating bacteria which typically range in size from 1 to 5 μm, it may be able to capture agglomerations of bacteria or of solids that contribute to turbidity. In this way, sari-cloth filtration may effectively remove flocs formed during moringa coagulation, in doing so possibly enhancing its effectiveness. Combining moringa coagulation and sari-cloth filtration could be a simple, inexpensive and widely available pre-treatment for SODIS applications.

This study assesses the efficacy of a multi-stage POU water treatment system combining sari-cloth filtration and/or moringa coagulation with SODIS, using a contaminated surface water source taken from a peri-urban slum in Chennai, India. The suitability of sari-cloth filtration and/or moringa coagulation as a pre-treatment for SODIS is addressed. Turbidity, organic content and microbiological quality of treated water were assessed at various stages and configurations of the proposed treatment system.

METHODS

Setting

All research activities were conducted at the Environmental and Water Resources Engineering laboratories of the Indian Institute of Technology Madras (IITM) in Chennai, India. Water samples for this study were taken from a surface water body supplying a peri-urban slum (Mylai Balaji Nagar) in south Chennai, Tamil Nadu, India. The lake is a receiving body for run-off from surrounding neighbourhoods, and ongoing monitoring of the lake indicates that water quality is severely degraded with excessive levels of organics, turbidity and microbiological contamination (Ali & Philip 2010).

Study design

We obtained raw lake water and subjected it to three stages of treatment: moringa coagulation (at different dosages of coagulant), sari-cloth filtration and SODIS. We extracted samples for analysis prior to treatment and again after each treatment stage. We analysed for three parameters: turbidity, measured in nephelometric turbidity units (NTU), with a Eutech Instruments TB1000 Cyberscan WL Turbidimeter (Thermo Fisher Scientific, Navi Mumbai, India); organic content via the proxy measure of chemical oxygen demand (COD), measured in mg L^{-1}, following the standard laboratory method (APHA 2005); and microbiological quality via the proxy measure of total coliforms estimation using the most probable number (MPN) method, measured as the probable number of total coliform bacteria per 100 mL of sample water, following the standard laboratory method (APHA 2005). All readings were done in triplicate to ensure accuracy, and the results were averaged for reporting purposes.

A total of eight replicate experiments were conducted, three in May 2010 and five in October 2010. May in Chennai is characterized by clear skies, intense sunlight and high temperatures (i.e. ~45 °C) and humidity, whereas October is characterized by days of variable cloudiness and sunshine, scattered rains and moderate temperature (i.e. ~35 °C) and humidity. The experiments were sometimes conducted on days which were partly cloudy; however, the majority of experiments were performed on clear, sunny days. The experimental design is outlined in Figure 1.

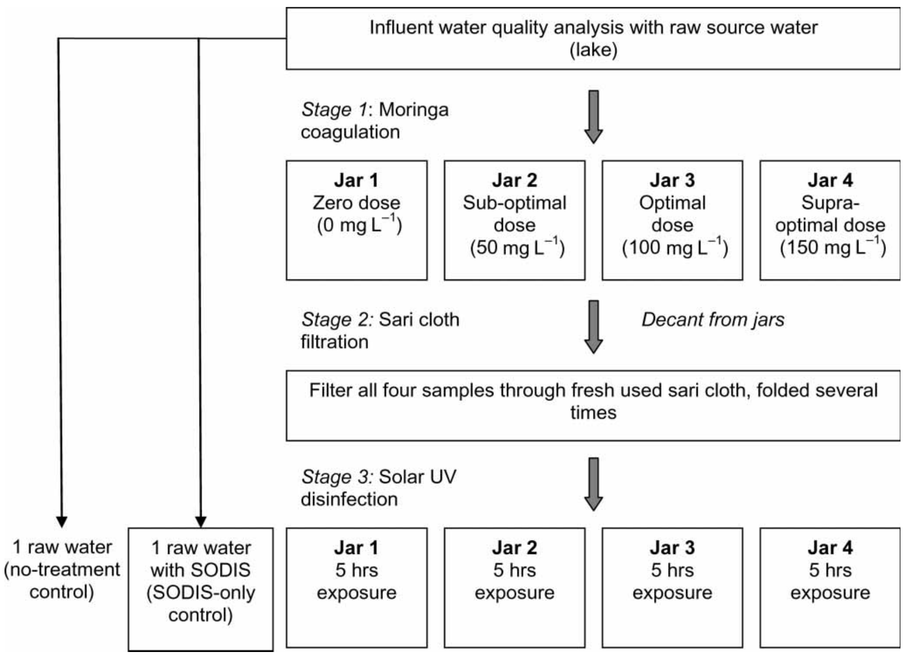

Figure 1 | Schematic representation of experimental design.

Preparation of moringa stock solution

Desiccated seeds of *Moringa oleifera* (var. PKM1) were obtained from the Regional Research Station in Paiyur, Krishnagiri District, Tamil Nadu, India. Following the procedure described by Lea (2010), the seeds were shelled and ground to a fine powder using a mortar and pestle and then sieved using a 0.4-mm mesh tea-strainer. The seed powder was then mixed with an appropriate volume of distilled water in a clean, re-sealable PET soft drink bottle in order to produce a 10,000 mg L^{-1} stock solution (by dry weight). Fresh stock solution was prepared the day of each replicate experiment.

Influent water sample collection

For each replicate experiment, we collected 20 L of raw lake water in 5-L plastic containers. The water was drawn from four different locations in the lake and mixed together in the lab in order to account for known spatial variability of lake water quality. A sample of the raw lake water was extracted after mixing for analysis to determine influent water quality.

Stage 1: moringa coagulation

Preliminary jar tests indicated 100 mg L^{-1} to be the optimal dose of moringa coagulant before diminishing turbidity reductions began to be observed with increasing coagulant dose. This is consistent with guidelines drawing on previous experience (Lea 2010). Four plastic beakers were each filled with 2 L of raw source water. Into each of the four jars a different volume of moringa stock solution was added. Jar 1 received no moringa stock solution and was thus a sari-cloth filtration-only control jar. Jars 2, 3 and 4 received a sub-optimal dosage (50 mg L^{-1}), an optimal dosage (100 mg L^{-1}) and a supra-optimal dosage (150 mg L^{-1}), respectively. The jars were then placed on a flocculator/jar test apparatus (Scientific Engineering Corporation Cat. No. SECOR 41, Delhi, India) and subjected to rapid mixing for 2 min at 100 rpm, followed by slow mixing for 20 min at 10 rpm, and finally settling under quiescent conditions for 1 h. Following settling, samples were decanted from each jar for analysis.

Stage II: sari-cloth filtration

Four sections of previously used cotton sari-cloth measuring 1 m × 2 m were washed with laundry soap and air-dried in the sun. Sari-cloths were folded four times to produce 16 layers of fabric and then secured with an elastic band over the openings of four clean beakers. Each jar from the previous stage was then decanted into the clean beakers through the sari-cloth filters. Following filtration, water samples were extracted for analysis.

Stage III: solar UV disinfection

Following sari-cloth filtration, the waters from the four beakers were placed in four clean 2-L PET bottles (i.e. common 2-L plastic soft drink bottles) and positioned in direct sunlight for 4–5 h on an inclined roof surface (Figure 2).

Though SODIS guidelines recommend a minimum exposure period of 6 h for sunny conditions (Wegelin *et al.* 1994; EAWAG 2010), only 4 to 5 h were possible during the present experiment because of the time required to complete the preceding experimental steps.

A SODIS-only control was prepared by filling a 1-L bottle with raw source water and subjecting it to the SODIS stage only, without moringa coagulation or sari-cloth filtration (Figure 3). Additionally, a sample of raw source water was collected at the end of the day and analysed as a no-treatment control.

Figure 2 | Bottles placed on inclined roof surface for SODIS stage.

Figure 3 | Bottles ready to be subjected to SODIS. L to R: SODIS-only control, sari-filtration-only control (Jar 1), sub-optimal moringa dose (Jar 2), optimal moringa dose (Jar 3) and supra-optimal dose (Jar 4).

Table 1 | Average values and standard deviation of influent water quality

	Mean	Standard deviation
Turbidity (NTU)	36.2	28.7
COD (mg L^{-1})	66.4	70.2
MPN (Total coliforms/100 mL)	113.2	54.7

Data analysis

All data were compiled in Microsoft Excel and analysed with the Analysis Toolpak for statistical difference between means using the one-tailed (unless otherwise indicated) paired *t*-test with $\alpha = 0.05$.

RESULTS AND DISCUSSION

As several replicate experiments were conducted, each on a unique day, the influent water quality was found to vary from trial to trial. Mean values for the three key water quality parameters and associated standard deviations are given in Table 1 in order to contextualize the local water quality.

To account for the variability in influent water quality observed between trials, all analytical results were normalized as a fraction of the influent concentration on the specific day of the replicate experiment. In Figures 4–7, the labels along the abscissa – MO, SF and UV – represent the water quality of the treated water after moringa coagulation (Stage I), after sari-cloth filtration (Stage II) and after UV disinfection (Stage III), respectively. The first set of bars on each graph, labelled as 'SW', represents the influent concentration of the source water and is thus normalized as 1. The two control samples – the no-treatment control and the SODIS-only control – were sampled after the final stage of treatment, UV (Stage III), and thus appear with the final set of bars on each graph. Finally, the number of replicate experiments aggregated in the summary measures is given by the *n* value

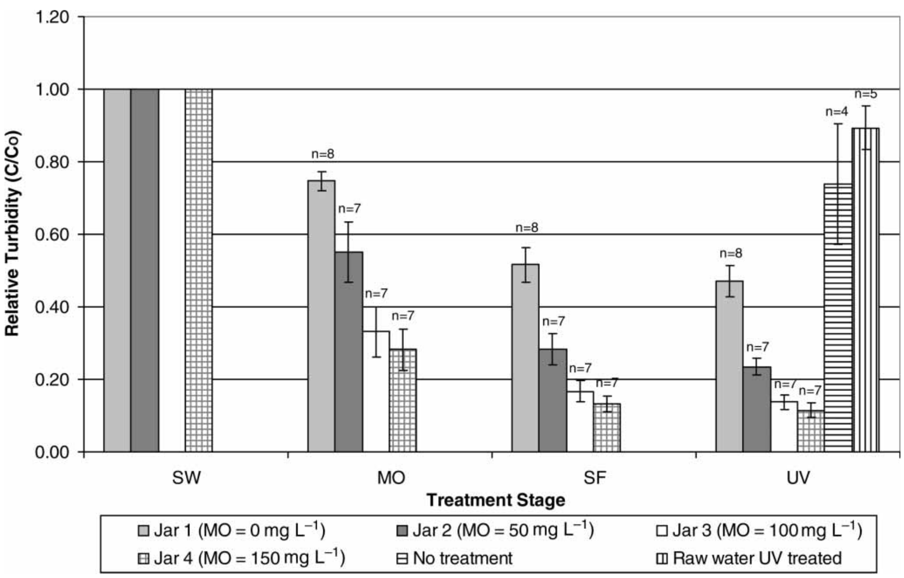

Figure 4 | Average turbidity removal efficacy of treatment.

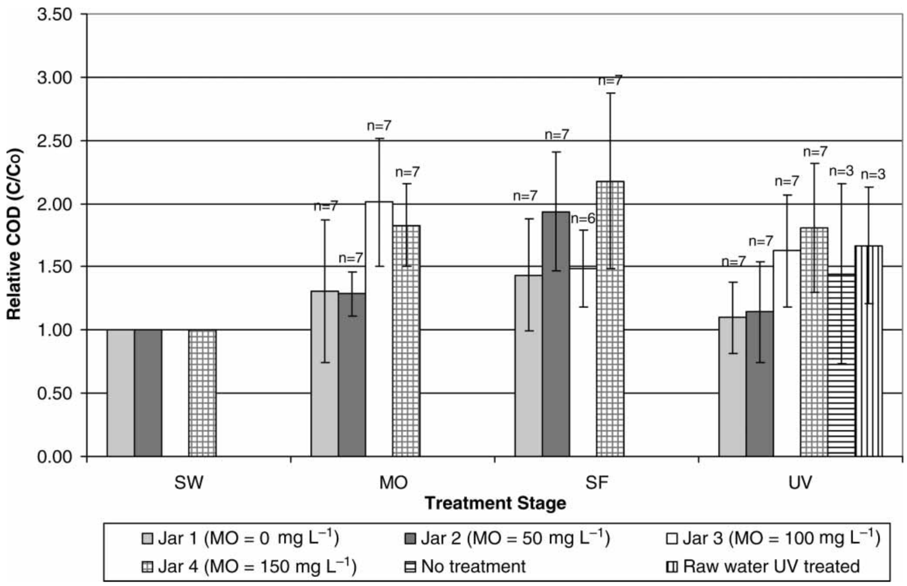

Figure 5 | Average effect of treatment process on COD, aggregated from several replicate trials (given by *n*).

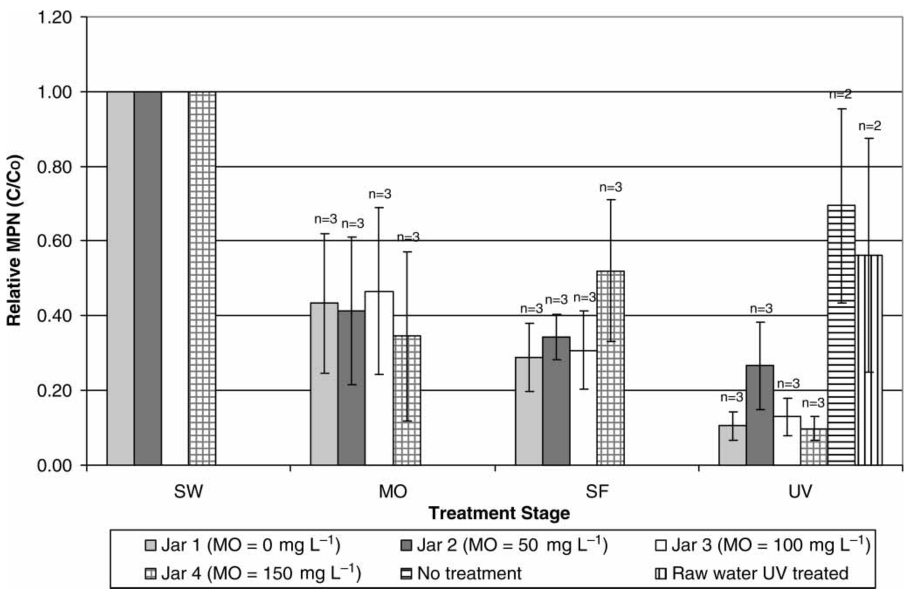

Figure 6 | Effect of treatment process on microbiological quality of water as represented by MPN.

indicated above each bar, and the error bars represent the standard error of the mean.

Turbidity reduction

Average turbidity reductions for each test jar, aggregated across all available replicate trials, are presented in Figure 4.

The final turbidity levels after the multi-stage treatment process, with associated 95% confidence intervals are given in Table 2.

In Figure 4, at any given treatment stage, it can be seen that with each progressive increase in moringa dosage, there is a corresponding reduction in turbidity. As expected, when the moringa concentration exceeds its optimal dose, there is

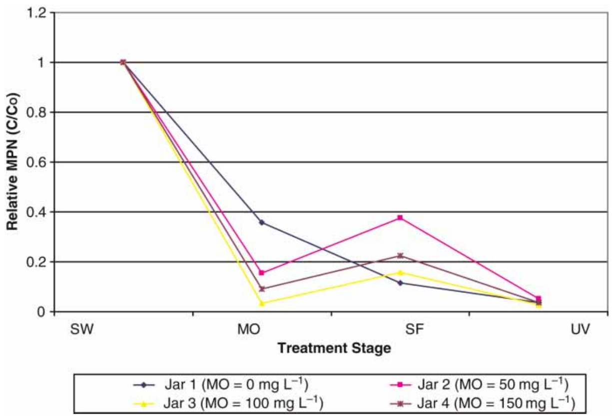

Figure 7 | MPN reduction efficacy of treatment process from the first of the eight replicate experiments.

Table 2 | Relative turbidity levels after multi-stage treatment process with associated 95% CI intervals

	Moringa jars				Controls	
Sample/jar	**1**	**2**	**3**	**4**	**No treatment**	**SODIS-only**
Relative turbidity	0.47	0.24	0.14	0.11	0.74	0.89
95% CI	0.10	0.05	0.05	0.05	0.53	0.17

a trend towards diminishing returns, as was also observed during the preliminary jar test. There also appear to be progressive reductions in turbidity after the moringa coagulation stage and then again after the sari-cloth filtration stage, suggesting that both of these treatments are effective at improving the turbidity of treated water. There is no apparent change in turbidity following the UV stage as SODIS is not expected to affect the turbidity of the water. Although it appears in Figure 4 that moringa coagulation with the optimal dose alone (MO Jar 3 – Relative reduction [RR]: 0.33) engenders a greater reduction in turbidity than does sari-cloth filtration alone (SF Jar 1 – RR: 0.52), the apparent superiority of moringa coagulation over sari-cloth filtration was not found to be statistically significant ($P = 0.06$, $n = 7$). However, combining optimal moringa coagulation and sari-cloth filtration (SF Jar 3 – RR: 0.17) does outperform sari-cloth filtration alone (SF Jar 1 – RR: 0.52) at a statistically significant level ($P = 0.0001$, $n = 7$). Likewise, sari-cloth filtration following optimal moringa coagulation (SF Jar 3 – RR: 0.17) significantly improved turbidity reduction compared to moringa coagulation alone (MO Jar 3 – RR: 0.33) ($P = 0.016$, $n = 7$). Both of these observations show that the combination of moringa coagulation and sari-cloth filtration is an effective means to improve turbidity, and the combination of the two is more effective at improving turbidity than either method by itself. The combined treatment chain of optimal moringa coagulation, sari-cloth filtration and SODIS (UV Jar 3 – RR: 0.14) significantly improved turbidity with respect to both the SODIS-only control (raw water UV-treated – RR: 0.9) ($P = 0.0002$, $n = 4$) and the blank control (No treatment – RR: 0.74) ($P = 0.006$, $n = 3$). Similarly, the jar receiving only sari-cloth filtration pre-treatment before SODIS (UV Jar 1 – RR: 0.47) significantly improved turbidity with respect to the control with no-pre-treatment before SODIS (Raw water UV-treated – RR: 0.9) ($P = 0.05$, $n = 5$).

Effect on organic content (COD)

The aggregated effect of the treatment process on the organics in the water, as measured by COD, is presented in Figure 5.

Final COD levels following the full treatment chain, with associated 95% confidence intervals, are given in Table 3.

Some comments can be made about the broad trends seen in Figure 5, albeit with the recognition that these are not statistically significant findings given the relatively high variability observed. COD levels appear to increase following the addition of moringa in the first stage of the treatment process. These levels remain relatively stable through the second sari-cloth filtration stage and then appear to decline following the final UV disinfection stage. The observed increase in COD levels was expected, given the introduction of organic material with the moringa solution, and has been observed by other workers

Table 3 | Relative COD levels following multi-stage treatment process with associated 95% CI intervals

	Moringa jars				Controls	
Sample	**1**	**2**	**3**	**4**	**No treatment**	**SODIS-only**
Relative COD	1.10	1.14	1.63	1.81	1.44	1.67
95% CI	0.69	0.97	1.08	1.25	3.06	1.98

(Ghebremichael *et al.* 2006; Arnoldsson *et al.* 2008). The non-statistically significant decline in COD levels following the SODIS stage may be explained by UV-mediated degradation of organic compounds (Wetzel *et al.* 1995). Those samples receiving greater concentrations of moringa displayed higher COD levels. For instance, after the final UV treatment stage, the jar receiving a moringa dose of 100 mg L^{-1} (UV Jar 3 – RR: 1.63) displayed more COD than that jar receiving only 50 mg L^{-1} (UV Jar 2 – RR: 1.14) ($P = 0.04$, $n = 7$). Extracting the seed oil and using only the press-cake for coagulation (which is as effective a coagulant) is one possible means to control the enrichment of organics in treated water (Lea 2010).

Effect on microbiological quality

The effect of the treatment process on the microbiological quality of the water was analysed with total coliform estimation using the MPN method. This method indicates the most probable number of total coliform bacteria per 100 ml of sample water. Aggregate results from replicate trials are presented in Figure 6.

The final MPN levels for each of the moringa jars and controls, after all three stages of the treatment chain, are presented in Table 4.

The lengths of the error bars in Figure 6 denote high levels of variability in the MPN data. Some comments may be made on the general trends observed in the means, with the recognition, however, that these trends were not found to be statistically significant. With each stage of treatment, there appears to be a progressive reduction in total coliform levels. Following the moringa coagulation stage there is an apparent decrease in the level of MPN for all moringa dosages, a slight decrease for most jars after sari-cloth filtration and then another decrease following UV treatment for all jars. As indicated in Table 4, the four treatment jars reduced MPN levels to between 10 and 27% of the influent level. The optimal moringa coagulation and sari-cloth filtration pre-treatment (UV Jar 3 – RR: 0.13) did not appear to significantly outperform pre-treatment with sari-cloth filtration alone (UV Jar 1 – RR: 0.11) ($P_{\text{two-tail}} = 0.41$, $n = 3$). Likewise, we cannot statistically conclude that either of the pre-treatments or their combined application had any effect on the microbiological content of the water with respect to the controls ($P \gg 0.05$ for all UV jars against controls). It has previously been reported that SODIS is less effective when applied to turbid waters (SANDEC 2008). Given that moringa and sari-cloth filtration were found to significantly improve turbidity, one would expect greater efficacy of SODIS as well with respect to MPN; however, the present data do not statistically support this conclusion.

An interesting feature can be observed in Jar 4 in the SF stage in Figure 6. The relative MPN level increases from 0.34 to 0.52 of the influent level in the 1 h of time elapsed between the moringa coagulation (MO) stage and the sari-cloth filtration (SF) stage, though this feature was not found to be statistically significant ($P = 0.06$, $n = 3$). This apparent re-growth was observed several times in the individual replicate experiments for all jars receiving a dose of moringa; however, due to the variability in the data, it is not visible in the aggregated data, the exception being Jar 4. The re-growth phenomenon can be more clearly seen in the disaggregated data from the individual trials – for instance, in the first of the eight replicate experiments (Figure 7).

As previously discussed, the application of moringa resulted in elevated COD levels (Figure 5). In Figure 7, re-growth of total coliform bacteria can be observed in those jars receiving some moringa, whereas Jar 1 – which does not receive any moringa – does not exhibit any re-growth, suggesting that the addition of moringa may encourage bacterial re-growth in treated waters. The natural organic material introduced with the moringa coagulant may act as a nutrient source, encouraging the growth of various bacteria species. One would assume that the more moringa that is added, the higher the organics content would become, leading to more bacterial re-growth. This expectation is not observed in Figure 7, as Jar 2 – with only 50 mg L^{-1} of moringa – seems to result in more re-growth than either Jars 3 or 4, which both received more moringa. However, Figure 7 presents only a single replicate experiment, so the

Table 4 | Relative MPN levels following multi-stage treatment process with associated 95% CI intervals

	Moringa jars				Controls	
Sample	**1**	**2**	**3**	**4**	**No treatment**	**SODIS-only**
Relative MPN	0.11	0.27	0.13	0.10	0.69	0.56
95% CI	0.16	0.51	0.22	0.14	3.30	3.96

expected trend may be obscured by experimental error. When examining the data aggregated from all eight replicate experiments, however, the expected trend can be seen visually on the graph, but is not statistically significant. The enrichment of the water with organics following moringa addition may explain why Jar 4, having received the greatest dose of moringa, displayed the apparent but statistically insignificant bacterial re-growth in Figure 6 between the moringa coagulation (MO) stage and the sari-cloth (SF) filtration stage. Furthermore, re-growth facilitated by nutrient enrichment may help to explain why optimal moringa coagulation with sari-cloth filtration (Jar 3) did not outperform sari-cloth filtration alone (Jar 1) with respect to microbiological quality. Although moringa coagulation reduces turbidity more effectively than simple filtration, it does so at the cost of increasing the organic content and, possibly, the total coliform levels. It should be noted, however, that the re-growth of total coliform bacteria does not necessarily indicate the re-growth of pathogenic bacteria (EAWAG 2010). Further research is needed to better characterize the relationship between organic content and microbiological re-growth during household-level moringa coagulation.

CONCLUSIONS

SODIS has been advocated as a simple, low-cost and effective means of improving the microbiological quality of water and has several benefits over household chlorination. However, like chlorination, its effectiveness is limited when waters are turbid and, as such, pre-treatments to control turbidity may be necessary. The present study sought to examine two low-cost, appropriate pre-treatment methods: sari-cloth filtration and/or coagulation with desiccated seed powder of *M. oleifera*. Pre-treatment combining optimal moringa coagulation and sari-cloth filtration significantly improved the turbidity of raw surface water compared to controls, as did either pre-treatment alone compared to controls. More importantly, however, combining optimal moringa coagulation with sari-cloth filtration significantly improved the turbidity reduction that either sari-cloth filtration or optimal moringa coagulation could achieve independently. The addition of moringa seed powder also appeared to increase organic levels (as measured by COD) in treated water, with greater doses of moringa resulting in higher COD levels. Similarly, reductions in microbiological contamination (as measured by MPN/100 mL) to between 10 and 27% of influent levels were observed for all jars subject to pre-treatment; however, due to considerable variability in the data, this apparent improvement was not found to be statistically significant when compared to controls. It was observed, however, that jars also undergoing moringa coagulation did not outperform those undergoing sari-cloth filtration alone with respect to MPN levels. Nutrient enrichment may have resulted in coliform bacteria re-growth following coagulation with moringa, which was observed in several replicate trials, though was not found to be statistically significant in the aggregated data. The possible re-growth of total coliform bacteria may be associated with elevated COD levels, as greater re-growth appeared to be associated with higher doses of moringa coagulant, though this also could not be confirmed statistically. Further investigation on the relationship between organic content and microbiological re-growth in treated water is required before moringa coagulation can be recommended as a pre-treatment for SODIS in the field.

Overall, the combined pre-treatment of moringa coagulation and sari-cloth filtration was the most effective at reducing turbidity. However, the moringa coagulation step adds significant complexity to the treatment process and increases the time, effort and materials required on the part of the household. Training illiterate or semi-literate households to carry out moringa coagulation and then ensuring compliance may prove challenging. On the other hand, sari-cloth filtration alone produced a significant reduction in turbidity with respect to controls. It is a simple technique that is already widely available and practised in the Indian context. Since sari-cloth filtration alone did not increase COD levels nor exhibit associated bacterial re-growth, it is recommended as a low cost, easy-to-use and readily available pre-treatment for SODIS.

ACKNOWLEDGEMENTS

This work was carried out with the aid of a grant from the International Development Research Centre (IDRC), Ottawa, Canada. The authors would also like to thank the two anonymous reviewers for their assistance with improving this manuscript.

REFERENCES

Achuthan, K. 2006 Clean water at no cost, the SODIS way. *The Hindu*. e-newspaper Thursday September 14 2006. Available from: http://www.hundu.com/2006/09/14/stories/2006091419 (accessed 1 December 2010).

Ali, S. I. 2010 Alternatives for safe water provision in urban and peri-urban slums. *J. Water Health* **8** (4), 720–734.

Ali, S. I. & Philip, L. 2010 Unsafe waters and degraded environments: pressing public health challenges in under-privileged urban and peri-urban communities – the case of Mylai Balaji Nagar, Chennai. In: *National Conference on Cost Effective Sustainable Sanitation – An Indian Experience*. New Delhi, India.

APHA 2005 *Standard Methods for the Examination of Water and Wastewater 21st edition*. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC.

Arnoldsson, E., Bergman, M., Matsinhe, N. & Persson, K. M. 2008 Assessment of drinking water treatment using Moringa oleifera natural coagulant. *Vatten* **64**, 137–150.

Babu, R. & Chaudhuri, M. 2005 Home water treatment by direct filtration with natural coagulant. *J. Water Health* **3** (1), 27–30.

Boyle, M., Sichel, C., Fernández-Ibáñez, P., Arias-Quiroz, G. B., Iriarte-Puña, M., Mercado, A., Ubomba-Jaswa, E. & McGuigan, K. G. 2008 Bactericidal effect of solar water disinfection under real sunlight conditions. *Appl. Environ. Microbiol.* **74** (10), 2997–3001.

Colwell, R. R., Huq, A., Islam, M. S., Aziz, K. M. A., Yunus, M., Khan, N. H., Mahmud, A., Sack, R. B., Nair, G. B., Chakraborty, J., Sack, D. A. & Russek-Cohen, E. 2003 Reduction of cholera in Bangladeshi villages by simple filtration. *Proc. Natl Acad. Sci. USA* **100** (3), 1051–1055.

Conroy, R. M., Meegan, M. E., Joyce, T., McGuigan, K. & Barnes, J. 1999 Solar disinfection of water reduces diarrhoeal disease: an update. *Arch. Dis. Child.* **81** (4), 337–338.

EAWAG 2010 SODIS: How does it work? *SODIS Method*. p. 1. Available from: http://www.sodis.ch/methode/anwendung/index_EN (accessed 2 October 2010).

Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L. & Colford, J. M. 2005 Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *Lancet Infect. Dis.* **5**, 42–52.

Firth, J., Balraj, V., Muliyil, J., Roy, S., Rani, L. M., Chandresekhar, R. & Kang, G. 2010 Point-of-use interventions to decrease contamination of drinking water: a randomized, controlled pilot study on efficacy, effectiveness, and acceptability of closed containers, moringa oleifera, and in-home chlorination in rural South India. *Am. J. Trop. Med. Hyg.* **82** (5), 759–765.

Fisher, M. B., Keenan, C. R., Nelson, K. L. & Voelker, B. M. 2008 Speeding up solar disinfection (SODIS): effects of hydrogen peroxide, temperature, pH, and copper plus ascorbate on the photoinactivation of *E. coli*. *J. Water Health* **6** (1), 35–51.

Freeman, M. C., Quick, R. E., Rheingans, R. & Abbott, D. P. 2005 Removing barriers to point-of-use water treatment products through social marketing and entrepreneurship: a case study in Western Kenya. *World Health Organization, Household Water, Treatment and Storage Conference*, Bangkok, Thailand, June 2005.

Ghebremichael, K. A., Gunaratna, K. R. & Dalhammar, G. 2006 Single-step ion exchange purification of the coagulant protein from Moringa oleifera seed. *Appl. Microbiol. Biotechnol.* **70** (5), 526–532.

Gómez-Cousoa, H., Fontán-Sainza, M., McGuigan, K. G. & Ares-Mazás, E. 2009 Effect of the radiation intensity, water turbidity and exposure time on the survival of Cryptosporidium during simulated solar disinfection of drinking water. *Acta Tropica* **112** (1), 43–48.

Gupta, A. 2004 Drinking water quality in Barak Valley, Assam, North East India: prioritizing management options. In: *Proceedings of the 2nd APHW Conference*. Asia Pacific Association of Hydrology and Water Resources, Singapore, pp. 1–7.

Hijnen, W. A. M., Beerendonk, E. F. & Medema, G. J. 2006 Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: a review. *Water Res.* **40** (1), 3–22.

Hunter, P. R. 2009 Household water treatment in developing countries: comparing different intervention types using meta-regression. *Environ. Sci. Tech.* **43** (23), 8991–8997.

Huq, A., Xu, B., Chowdhury, M. A. R., Islam, M. S., Montilla, R. & Colwell, R. R. 1996 A simple filtration method to remove plankton-associated Vibrio cholerae in raw water supplies in developing countries. *Appl. Environ. Microbiol.* **62** (7), 2508–2512.

Huq, A., Yunus, M., Sohel, S. S., Bhuiya, A., Emch, M., Luby, S. P., Russek-Cohen, E., Nair, G. B., Sack, R. B. & Colwell, R. R. 2010 Simple sari cloth filtration of water is sustainable and continues to protect villagers from cholera in Matlab, Bangladesh. *mBio* **1** (1), 1–5.

Joyce, T. M., McGuigan, K. G., Elmore-Meegan, M. & Conroy, R. M. 1996 Inactivation of fecal bacteria in drinking water by solar heating. *Appl. Environ. Microbiol.* **62** (2), 399–402.

Lea, M. 2010 Bioremediation of turbid surface water using seed extract from Moringa oleifera Lam. (drumstick) tree. *Current Protocols in Microbiology* Chapter 1 (February), Unit 1G.2.

Lonnen, J., Kilvington, S., Kehoe, S. C., Al-Touati, F. & McGuigan, K. G. 2005 Solar and photocatalytic disinfection of protozoan, fungal and bacterial microbes in drinking water. *Water Res.* **39** (5), 877–883.

Madsen, M., Schlundt, J. & Omer, E. F. 1987 Effect of water coagulation by seeds of Moringa oleifera on bacterial concentrations. *J. Trop. Med. Hyg.* **90** (3), 101–109.

Murphy, H. M., McBean, E. A. & Farahbakhsh, K. 2009 Appropriate technology – A comprehensive approach for water and sanitation in the developing world. *Tech. Soc.* **31** (2), 158–167.

Nkurunziza, T., Nduwayezu, J. B., Banadda, E. N. & Nhapi, I. 2009 The effect of turbidity levels and Moringa oleifera concentration on the effectiveness of coagulation in water treatment. *Water Sci. Tech.* **59** (8), 1551–1558.

Oluduro, A. O. & Aderiye, B. I. 2007 Efficacy of Moringa oleifera seed extract on the microflora of surface and underground water. *J. Plant Sci.* **2** (4), 453–458.

Preston, K., Lantagne, D., Kotlarz, N. & Jellison, K. 2010 Turbidity and chlorine demand reduction using alum and moringa flocculation before household chlorination in developing countries. *J. Water Health* **8** (1), 60–70.

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.

Rose, A., Roy, S., Abraham, V., Holmgren, G., George, K., Balraj, V., Abraham, S., Muliyil, J., Joseph, A. & Kang, G. 2006 Solar disinfection of water for diarrhoeal prevention in southern India. *Arch. Dis. Child.* **91** (2), 139–141.

SANDEC 2008 *SODIS Technical Note #7: Water Quality: Turbidity and Water Depth*. Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland.

Sobsey, M. D. 2002 *Managing Water in the Home: Accelerated Health Gains from Improved Water Supply*. World Health Organization, Geneva, Switzerland.

Wegelin, M., Canonica, S., Mechsner, K., Fleischmann, T., Pesaro, F. & Metzler, A. 1994 Solar water disinfection: scope of the process and analysis of radiation experiments. *AQUA* **43** (4), 154–169.

Wetzel, R. G., Hatcher, P. G. & Bianchi, T. S. 1995 Natural photolysis by ultraviolet irradiance of recalcitrant dissolved organic matter to simple substrates for rapid bacterial metabolism. *Limnol. Oceanogr.* **40** (8), 1369–1380.

Wilson, S. & Andrews, S. A. 2010 Impact of water quality on solar disinfection (SODIS): investigating a natural coagulant pretreatment. In: Presentation at the *Water and Health: Where Science Meets Policy Conference* (Oct. 25–26, 2010). University of North Carolina at Chapel Hill, Chapel Hill, NC, USA.

First received 1 December 2010; accepted in revised form 19 March 2011