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Optimizing the Solar Water Disinfection (SODIS) Method by Decreasing Turbidity with NaCl

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Abstract.

Solar water disinfection (SODIS) has proven to be effective at reducing diarrheal incidence in epidemiological intervention studies. However, the SODIS method is limited to waters of low turbidity (<30NTU). This study investigates the use of common table salt (NaCl) to reduce the turbidity of water containing suspended colloidal clay particles for use in the SODIS method. Three representative clays found in tropical soils (kaolinite, illite, and bentonite) were tested at three levels of turbidity (50, 100, and 200 NTU) for their flocculating behaviour with multiple NaCl concentrations to find the optimum. Supernatants were tested for sodium concentration for comparison against health and taste thresholds. Results show that unlike kaolinite and illite, pure bentonite solutions were shown to be very responsive to NaCl and produced supernatants with as low as 4 NTU (98% particle removal efficiency). This study has shown that NaCl, in combination with high-activity clay particles in solution, may effectively reduce turbidity to levels suitable for SODIS treatment, thereby expanding the number of people who can utilize the technology effectively.

Keywords: clay, drinking water, flocculation, sanitation, SODIS, sodium, turbidity

Introduction

The overwhelming number of people without adequate access to clean water for drinking and sanitation purposes calls for the provision of an appropriate method of treating microbiologically contaminated water (World Health Organization 2010). Solar water disinfection (SODIS) has been proven in both bench and field scale trials to significantly reduce microbial content in contaminated water, and associated incidence of diarrhea in users (Centre for Disease Control 2008; Graf et al. 2010; Meierhofer 2006; World Health Organization 2002). However, the technology is limited to relatively clear water (with turbidity less than 30 nephalometric turbidity units [NTU]); therefore, there is significant need to provide a practical method of reducing turbidity in water prior to solar disinfection.

This study investigates the use of a common reagent, table salt (NaCl), in facilitating the settling of colloidal clay particles in water, with the aim of expanding the availability of the SODIS technology. First, the SODIS method is reviewed along with the effects of turbidity, colloidal particles and sodium content. Then, three representative clays found in tropical soils (kaolinite, illite, and bentonite [sodium form]) were tested at three levels of turbidity (50, 100, and 200 NTU) for their flocculating behaviour with five concentrations (0.001 M, 0.005 M, 0.01 M, 0.05 M, and 0.1 M) of NaCl. The supernatant was tested for remaining sodium concentration for comparison against health and taste thresholds. The results are then reviewed, discussed and conclusions are drawn about the viability of NaCl in reducing turbidity in waters containing colloidal clay particles.

Background

Solar Water Disinfection

Although specialized methods are needed to appropriately purify chemical contamination of drinking water supplies in poor regions (Hashmi & Pearce, 2011), one of the most technically simple, affordable, and practical systems for disinfecting microbiologically-contaminated water is the solar water disinfection (SODIS) system (World Health Organization 2002). This system treats contaminated water by inactivating microorganisms through a synergistic combination of optical and thermal processes and requires only a transparent container (Meierhofer & Wegelin 2002). As it employs point-of-use treatment, the clean water can be used and stored with a reduced risk of secondary contamination. Furthermore, at an annual cost of US$0.40-US$3.00, depending on location, it is an extremely low-cost water treatment method (Meierhofer & Landolt 2008; World Health Organization 2002) and is one of the most inexpensive household treatments available (Clasen et al. 2007).

The inactivation of select bacteria, viruses, and protozoa due to UV-A radiation and heat has been studied extensively in studies under both simulated and natural conditions (Berney et al. 2006; Boyle et al. 2008; Dejung et al. 2007; Gómez-Couso 2009; Heaselgrave et al. 2006; Joyce et al. 1996; Méndez-Hermida 2007; McGuigan et al. 1998; Rijal & Fujioka 2001). It has been shown that a synergistic effect in low-turbidity water is observed when water temperature exceeds 45^{o}C, at which point the combined inactivation effectiveness is greater than the individual contributions of radiation and heat (McGuigan et al. 1998). The effectiveness of the SODIS method at decreasing diarrheal incidence has also been investigated in epidemiological intervention studies and has proven to be credible: a decrease in diarrhea incidence by as much as 86% has been observed (Centre for Disease Control 2008; Graf et al. 2010; Meierhofer 2006; World Health Organization 2002). The method has shown to be particularly effective at reducing diarrhea in children under the age of five (Conroy et al. 1995; 1996; 1999; 2001; Graf et al. 2010; Rai et al. 2010; Rose et al. 2006).

The Effect of Turbidity

The World Health Organization has stated that treating turbid water is “a special concern”, as turbidity particles shield the UV radiation that inactivates microbes in the water (World Health Organization 2002), which compromises the effectiveness of the SODIS treatment process. Numerous microbiological studies have revealed that highly turbid waters do not allow for the previously mentioned synergistic effect to occur (Gómez-Couso et al. 2009; Kehoe et al. 2001; McGuigan et al. 2008). Treatment of highly turbid waters is possible, but requires achieving temperatures of at least 55^{o}C (Joyce et al. 1996). At such high temperatures and high turbidity, inactivation occurs by pasteurization; that is, by thermal mechanisms only: McGuigan et al. (2008) showed that in highly turbid water (200 NTU), 99% inactivation of *E. coli* occurred only 1 cm into the optical path. There is therefore a significant need for a low-cost, practical method for reducing turbidity in source water prior to treatment by solar disinfection, which would allow for faster treatment.

Suspended colloidal particles

Relatively large and dense solid particles have settling velocities high enough such that they will settle in aqueous solution due to gravity. However, colloidal particles remain suspended due to their small size and (generally) electronegative surface charge. One method of inducing the settling of colloidal particles is through the process of coagulation-flocculation, by which colloids are destabilized and aggregated, ultimately resulting in their removal. The use of polyelectrolytes to facilitate coagulation-flocculation has been studied and applied extensively, especially in the treatment of suspended particles in industrial water and wastewater treatment processes. Mainly the polyelectrolytes alum and ferric salts are used (Alaerts & Van Haute 1983), due to their high valence charge, which facilitates adsorption onto the colloidal particle (Alaerts & Van Haute 1981; Juo 2003). The use of coagulation-flocculation in water treatment in developing countries has been tested and proven to be effective; however, the availability of these chemicals and relatively high cost place this treatment method beyond the means of many people (World Health Organization 2002). The use of *Moringa Oleifera* has shown to be effective at reducing turbidity as well as improving microbial quality in water (Nkurunziza et al. 2009; Pritchard et al. 2009; Ferreira et al. 2011); however, it is not available in all regions of concern and the process requires extraction of the lectin from the seed.

Sodium content

For acclimatized adults, the physiological need for sodium is 184-230 mg/day (Dahl 1972), attainable by consuming about 460-575 mg/day of NaCl. However, average daily sodium intake values vary across countries, age, and gender (Elliot & Brown 2007). Tolerable limits and reference values vary similarly. For the purpose of this study, the tolerable upper limit of daily salt intake for North Americans of 5800 mg, corresponding to approximately 2400 mg of sodium (Food and Nutrition Board, 2004), was used as a maximum allowable limit for a user's intake of sodium due to water treated with NaCl. Based on data from North American men and women, it is recommended that the average healthy adult male consumes 3.7 L/day of water from all sources (food and drinking water), and women should consume on average 2.7 L/day (Food and Nutrition Board 2004). This implies that for a SODIS user consuming the North American average of 3.7 and 2.7 L/day of water treated with the proposed NaCl method, the sodium content must not exceed 650 mg/L for men and 890 mg/L for women, and should be as low as possible so as to allow intake of sodium through food. It should be acknowledged that SODIS users are likely to consume less drinking water and salt than the North American reference values. The taste threshold for NaCl in water is approximately 640 mg/L (Wiesenthal et al. 2007); therefore, concentrations in the supernatant should not exceed this value, which corresponds to approximately 256 mg/L of sodium

Research goals

This bench-top experiment investigates the effectiveness of a readily available electrolyte, sodium chloride (NaCl) in reducing turbidity in waters due to colloidal clay particles. The flocculating behaviour of different types of clay in saline solutions has been documented (Akther et al. 2008; Gibbs 1983; 1985; Hsi & Clifton, 1960; Panayiotopoulos et al. 2004). Furthermore, there is potential for the well-known flocculating behaviour of clays to apply to complex clay and mud combinations (Mietta et al. 2009). The effectiveness of NaCl at reducing turbidity due to colloidal clay particles in the context of household water treatment may significantly impact the availability of SODIS as a household water treatment option in developing countries.

Methodology

Preparation of turbid samples

The following types of clays were tested for their flocculating behaviour with NaCl: kaolinite, illite, and sodium bentonite, which naturally occur tropical soils (Gómez-Couso et al., 2009; Juo 2003). The preparation of the turbid samples followed that outlined by Gómez-Couso et al. (2009). Soil was added to 1000 ml of distilled water to obtain turbidity levels of 50, 100, and 200 NTU, covering a wide range of possible field conditions as outlined by McGuigan et al. (1998).

Concentrations of NaCl

Five different concentrations of NaCl were tested originally in order to find the range in which the optimal concentration exists. These concentrations were 0.001 M, 0.005 M, 0.01 M, 0.05 M, and 0.1 M, corresponding to 0.0584 g, 0.2922 g, 0.5844 g, 2.922 g, and 5.844 g of NaCl per liter, respectively. Once the minimum concentration that produced a supernatant of <30 NTU was found, the range in which the optimal concentration lies was narrowed to between 0.5844 g and 2.922 g. Further testing was then conducted to determine the optimal amount of NaCl using concentrations of 0.013 M, 0.017 M, 0.021 M, 0.026 M, 0.030 M, and 0.034 M, corresponding to 0.75 g, 1.00 g, 1.25 g, 1.50 g, 1.75 g, and 2.00 g of NaCl per liter of water.

Coagulation-flocculation with NaCl

Standard jar test experiments were conducted to determine the flocculating behaviour of NaCl with each type of clay, as outlined in the ASTM Standard Practice for Coagulation-Flocculation Jar Test of Water (D2305-08). Temperature was held constant at 21 ± 0.5^{o}C. Samples were flash-mixed for a period of 1 minute at 130 rpm and then underwent slow-mix at 15 rpm for a period of 20 minutes. Samples were then allowed to settle for 60 minutes, and qualitative and quantitative observations were recorded at 15-minute increments. Turbidity was measured with a portable Orbeco turbidimeter and is expressed in NTU, following the procedure outlined in the ASTM Standard Test Method for Determination of Turbidity Above 1 Turbidity Unit (D7315-07a). pH was monitored with a Fisher Accumet 1003N portable pH meter.

Quantity of sodium ions present in supernatant

25 ml of supernatant was collected at a depth of 60 mm and then heated to 90^{o}C for 300 minutes with 2 ml of 1.0 M HNO_3 to ensure any solids were completely dissolved in the solution. Quantitative inductively coupled plasma by optical emission spectroscopy (ICP-OES) analysis of the sodium ions present in the supernatant was then performed with a Varian Vista AX CCD Simultaneous ICP-AES.

The entire procedure was repeated for a second suite of trials.

Results

Changes in turbidity

NaCl in pure solutions of bentonite was found to be very effective and demonstrated as high as 98% removal efficiency as can be seen in Figure 1. For solutions of kaolinite and illite, NaCl was effective at reducing turbidity to below the 30 NTU SODIS threshold only when the initial turbidity was 50 NTU, corresponding to a maximum removal efficiency of 50%. All data points shown are the average of three measurements with the turbidimeter, corresponding to a maximum error of 5.5%.

Figure 1 illustrates the settling kinetics of pure bentonite suspensions for: a) 50 NTU, b) 100 NTU, and c) 200 NTU. The eye-guide horizontal line at 30 NTU is the SODIS limit and the concentrations of salt that exceed the allowable limit are marked with an asterisk.

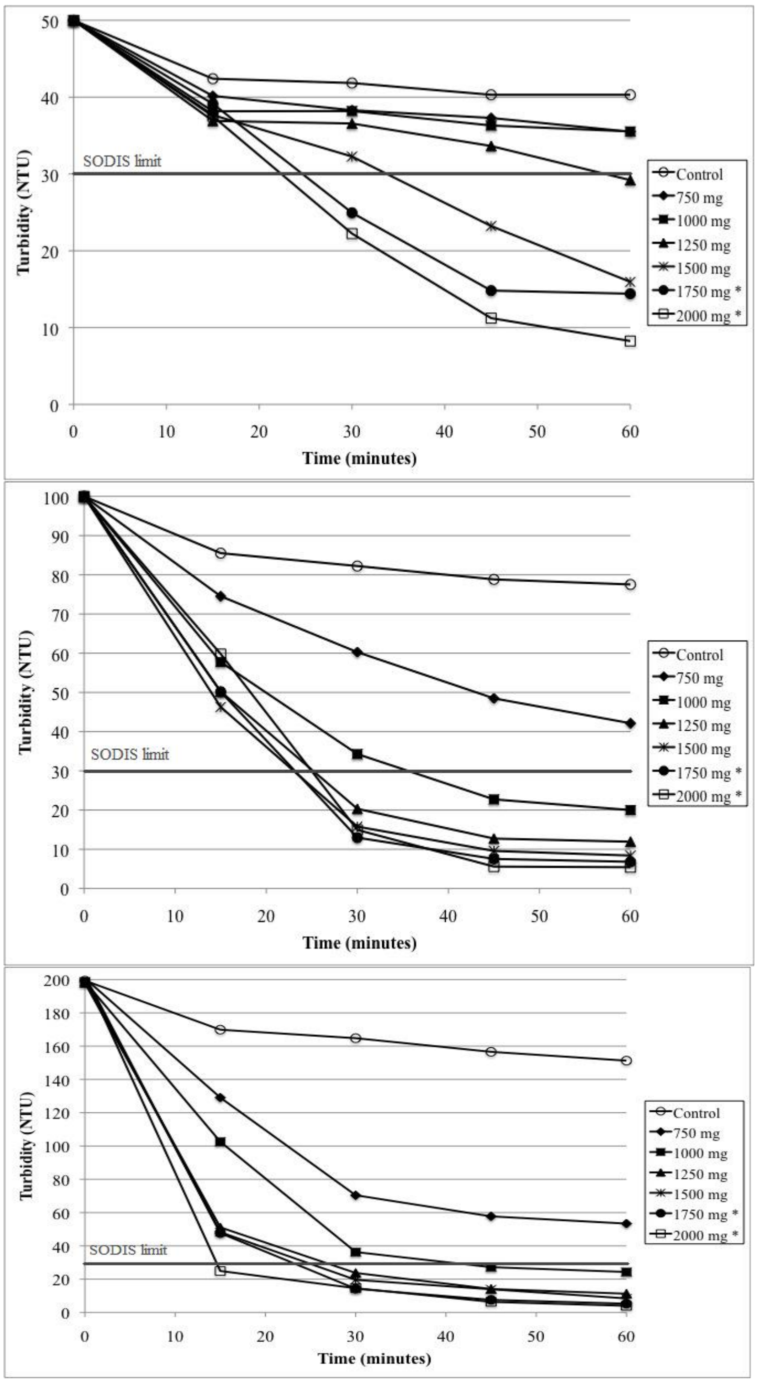

Figure 1. Settling kinetics of 100% bentonite suspensions from an initial turbidity of a) 50 NTU, b) 100 NTU, and c) 200 NTU. The concentrations marked with an asterisk resulted in supernatants with a sodium concentration that exceeds allowable limits.

Changes in pH

For varying initial turbidity levels, initial pH ranged from 6.3 to 8.1 for bentonite solutions, 5.1 to 5.8 for illite solutions, and 5.2 to 5.8 for kaolinite solutions, reflecting the natural alkalinity and acidity of these types of clays. Overall it was found that pH varied at most by 0.4 over the course of settling, decreasing slightly for solutions of bentonite and increasing slightly for solutions of kaolinite and illite.

Sodium concentration in supernatant

Figure 2 illustrates the concentration of sodium remaining in the supernatant of suspensions that settled below the SODIS threshold of 30 NTU in 60 minutes.

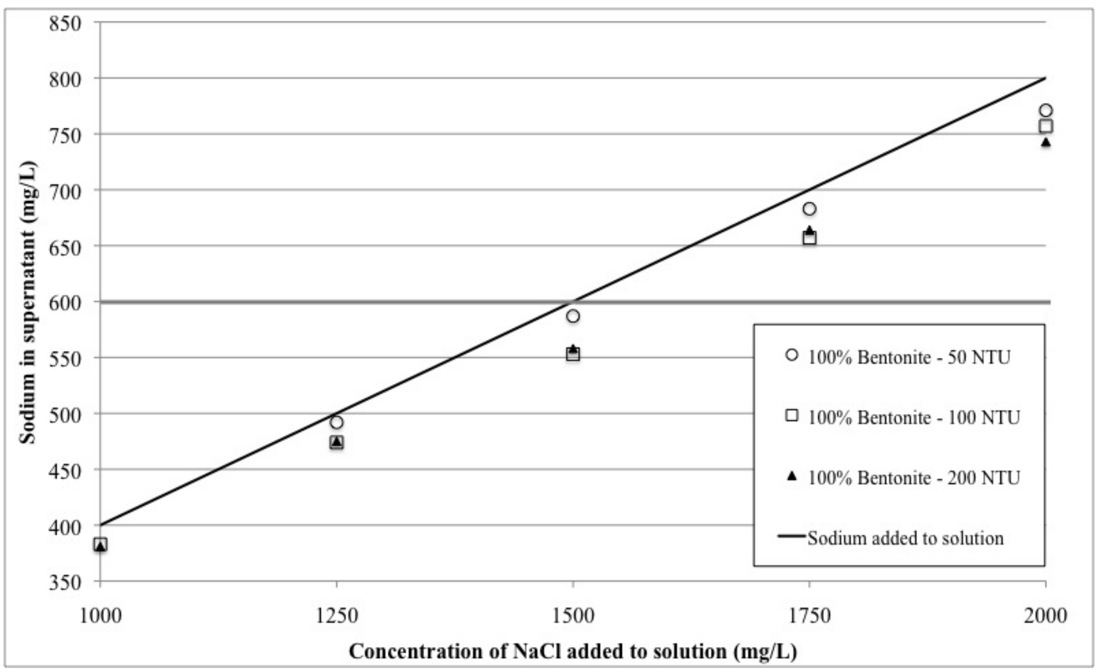

Figure 2. Sodium content remaining in supernatant after 60 minutes of settling with a final turbidity of less than 30 NTU.

As shown in Figure 2, ideal results tend toward the lower left-hand quadrant. The solid horizontal line denotes the maximum health limit based on an intake of 2400 mg of sodium per day.

Discussion

Effectiveness of NaCl at reducing turbidity

The results show that NaCl can be used to effectively reduce turbidity in water containing colloidal particles of high-activity clays such as sodium bentonite. This is because when NaCl is added to a suspension of sodium bentonite particles, the accumulation of sodium ions decreases the thickness of the electric double layer and reduces the hydration of the clay particles, causing flocculation (Roscoe Moss Company 1990). Kaolinite and illite were not as responsive to the addition of NaCl in the solution due to their relatively low cation exchange capacity (CEC) and mineral structure. Turbid source water containing these types of colloidal particles is likely not suitable for treatment with NaCl.

For pure bentonite with an initial turbidity of 50 NTU, 1250 mg/L of NaCl was required to facilitate settling to below the SODIS threshold. However, only 1000 mg/L of NaCl was required for suspensions with an initial turbidity of 100 and 200 NTU. Furthermore, greater percent reductions in turbidity were observed for samples with a relatively high initial turbidity, consistent with flocculation-coagulation mechanisms and the “jumpstart” effect that has been applied in industrial wastewater treatment, in which bentonite is added to turbid solutions to more efficiently facilitate flocculation (Yang et al. 2007). The results also suggest that water with an initial turbidity greater than 200 NTU may possibly be treated with these concentrations of NaCl with desirable results.

Sodium content

Though a range of NaCl concentrations produced supernatant turbidities below the SODIS threshold of 30 NTU, only those that satisfy health and taste limits may be considered as suitable for subsequent use as drinking water. As shown in Figure 2, a maximum concentration of 1500 mg/L of NaCl could be used without exceeding the allowable limit of 600 mg/L of sodium in the supernatant; therefore, only those solutions in which a maximum of 1500 mg/L of NaCl was added may be considered for drinking water use. While none of the supernatants contained sodium below the taste threshold of 256 mg/L, several fell below the sodium content in Gatorade (~460 mg/L), which suggests that certain solutions may be suitable for drinking water. Even if certain samples of water treated with the current method may not be suitable for drinking purposes, all of them may potentially be used for sanitation and hygiene purposes following SODIS treatment.

Implications of study

The results of the current study show that NaCl may be an effective means of reducing turbidity in water caused by naturally occurring high-activity colloidal clay particles. The results also suggest that NaCl, in combination with high-activity clay, may be used to treat turbid water according to the jumpstart effect utilized in industrial water treatment. Both implications may appreciably broaden the scope of people with access to SODIS as a household water treatment.

Future studies

It is recommended that the flocculating behaviour of NaCl with suspensions of calcium bentonite and magnesium bentonite be explored. Following these bench tests, field studies should be conducted in areas dominated by high-activity clays to determine if the results of bench tests are reproducible at the field scale and in relatively uncontrolled conditions. Studies should be conducted to explore the use of bentonite additives in combination with NaCl to produce a small-scale jumpstart effect. Optimization of this technology should be explored by determining the influence of controlled pH on settling. Furthermore, literature shows that bentonite has been used in the removal of contaminants in Sudan (Madsen & Schlundt 1989). Thus future work is needed to investigate the effectiveness of bentonite and NaCl combinations in removing microbiological contaminants. If the current method is deemed suitable for use in the field, a detailed cost analysis and life cycle analysis should be performed for comparison against other treatments. Further work must be done to explore and identify all possible health risks associated with this type of technology if the treated water is to be used for drinking purposes, particularly as they relate to sodium intake in various populations.

Conclusions

With appropriate social programming, SODIS has proven to be effective at reducing diarrheal incidence associated with microbiologically contaminated water in developing communities around the world. However, its synergistic mechanisms are limited to relatively clear water of less than 30 NTU; therefore, a simple and appropriate method of reducing turbidity prior to SODIS treatment may significantly expand the number of users with access to SODIS. This study has shown that NaCl, in combination with high-activity clay particles in solution, may effectively reduce turbidity to levels suitable for SODIS treatment. This may appreciably increase the number of people who can practice SODIS as a means of accessing clean water for sanitation purposes, and with some improvement, for drinking purposes. Future work should address the viability of this technology with different types of bentonite and at the field scale, as well as the effectiveness of bentonite and NaCl combinations at reducing microbiological content in water.

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