Turbidity and chlorine demand reduction using alum and moringa flocculation before household chlorination in developing countries

Kelsey Preston, Daniele Lantagne, Nadine Kotlarz and Kristen Jellison

ABSTRACT

Over 1.1 billion people in the world lack access to improved drinking water. Diarrhoeal and other waterborne diseases cause an estimated 1.87 million deaths per year. The Safe Water System (SWS) is a household water treatment intervention that reduces diarrhoeal disease incidence among users in developing countries. Turbid waters pose a particular challenge to implementation of SWS programmes; although research shows that a 3.75 $mg\,l^{-1}$ sodium hypochlorite dose effectively treats turbid waters, users sometimes object to the strong chlorine taste and prefer to drink water that is more aesthetically pleasing. This study investigated the efficacy of two locally available chemical water treatments—alum and *Moringa oleifera* flocculation—to reduce turbidity and chlorine demand at turbidities of 10, 30, 70, 100 and 300 NTU. Both treatments effectively reduced turbidity (alum flocculation 23.0–91.4%; moringa flocculation 14.2–96.2%). Alum flocculation effectively reduced chlorine demand compared with controls at 30, 70, 100 and 300 NTU ($p = 0.01$–0.06). Moringa flocculation increased chlorine demand to the point where adequate free chlorine residual was not maintained for 24 hours after treatment. Alum pretreatment is recommended in waters ≥ 30 NTU for optimum water disinfection. Moringa flocculation is not recommended before chlorination.

Key words | developing countries, drinking water, flocculation, household water treatment, *Moringa oleifera*, Safe Water System

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INTRODUCTION

Point-of-use water treatment and the Safe Water System

An estimated 1.1 billion people do not have access to improved water supplies (WHO/UNICEF 2004), and hundreds of millions more drink water contaminated during collection, transport and storage (Clasen & Bastable 2003). Diarrhoea accounts for 1.87 million (19%) childhood deaths each year (Boschi-Pinto *et al.* 2008).

Although small trials of point-of-use chlorination to reduce diarrhoeal disease had been implemented in the past (Mintz *et al.* 1995), larger-scale trials began in the 1990s as part of the Pan American Health Organization (PAHO) and the US Centers for Disease Control and Prevention (CDC) response to epidemic cholera in Latin America (Tauxe *et al.* 1995). The Safe Water System (SWS) strategy devised by CDC and PAHO includes three elements: water treatment with dilute (generally 1.25%) sodium hypochlorite at the point of use, storage of chlorinated water in a safe container, and behaviour change communication to improve hygiene and water and food handling practices. The sodium hypochlorite solution is packaged in a bottle with directions instructing users to add one full bottle cap (generally 3 ml) of the solution to clear water, or 2 caps to turbid water, in a standard sized (generally 20 l) storage container, agitate, and wait 30 minutes before drinking.

doi: 10.2166/wh.2009.210

Source waters treated with one or two full bottle cap(s) receive a dosage of 1.875 or 3.75 mg l^{-1} sodium hypochlorite, respectively. In six randomized, controlled trials, the SWS has resulted in reductions in diarrhoeal disease incidence ranging from 22 to 84% (Semenza *et al.* 1998; Quick *et al.* 1999, 2002; Reller *et al.* 2003; Luby *et al.* 2004; Crump *et al.* 2005).

This well-documented reduction of diarrhoeal disease incidence among SWS users has encouraged non-governmental organizations (NGOs) and governments to broadly disseminate the programme. Since 1998, national, regional and local SWS projects have been implemented with NGO and government partners in over 30 countries. As access to the SWS has expanded in developing countries, where many water sources contain suspended organic material, questions have been raised about: (1) the necessary sodium hypochlorite dosage for turbid waters; (2) user acceptability of treating turbid waters with sodium hypochlorite solution; and (3) potential locally appropriate mitigation strategies to reduce turbidity and chlorine demand before chlorination.

Sodium hypochlorite dosage in turbid waters

The CDC SWS programme aims for a free chlorine residual of less than 2.0 mg l^{-1} 1 hour after sodium hypochlorite addition and greater than 0.2 mg l^{-1} 24 hours after addition. This residual range was selected because it: 1) meets WHO and USEPA guidelines for free chlorine in drinking water (WHO/UNICEF 2004; USEPA 2006); 2) avoids user taste acceptability concerns above 2.0 mg l^{-1} free chlorine (Lantagne 2008); and 3) maintains free chlorine residual ≥ 0.2 mg l^{-1}, which will adequately protect water from recontamination. This dosage regime has been specifically approved as 'consistent with the Third Edition of the [WHO] Guidelines [for drinking-water quality]' (Bartram 2006). Results from dosage testing in 106 drinking water sources from 13 developing countries confirmed that 71 (86.6%) of 82 samples among non-chlorinated source water of turbidity less than 10 NTU or from a protected source met these guidelines when treated with 1.875 mg l^{-1} of sodium hypochlorite (Lantagne 2008). The results of dosage testing in the 14 non-chlorinated waters from unimproved sources with turbidity between 10 and 100 NTU were not as consistent: only five (41.7%) of the 12 sources analysed at the 3.75 mg l^{-1} dosage had free chlorine residuals that met the criteria. However, if the free chlorine residual criteria were relaxed to less than 3.5 mg l^{-1} one hour after sodium hypochlorite addition and greater than 0.1 mg l^{-1} 24 hours after addition, then 11 (91.7%) of the 12 sources analysed at the 3.75 mg l^{-1} dosage would have met these relaxed criteria. Further research on dosage and chlorine demand reduction in turbid waters was recommended.

User acceptability of turbid waters treated with sodium hypochlorite solution

Chlorine taste and odour are key concerns for user acceptability in SWS programmes. Many taste and odour concerns can be addressed by using dosage regimes that prevent overdosing (POUZN 2007). Focus groups on taste testing have found that the majority of SWS users are comfortable drinking water with a free chlorine residual of up to 2.0 mg l^{-1}; however, there is significant regional variation in the acceptable maximum residual (Lantagne 2008). The higher sodium hypochlorite dosages necessary to ensure maintenance of free chlorine residual in turbid waters exacerbate taste and odour concerns.

In addition, there is a commonly held perception that clear water is equivalent to clean, potable water (POUZN 2007). In the Population Services International (PSI) India SWS project, results from the baseline survey indicated that the majority of households agreed with the statement 'water that looks clear is safe to drink'. PSI/India conducted a multimedia campaign to communicate the message that clear water can be contaminated with microbes too small to be seen and that the SWS should be used in all waters stored in the home. Follow-up research documented a 20% reduction in the belief that water quality could be determined by appearance and a 25% increase in use of the SWS among respondents.

Locally available chemical water flocculation options

Several practical and inexpensive methods for water flocculation are available to populations in developing countries who are targeted by point-of-use water treatment intervention programmes such as the SWS. This study

Figure 1 | Alum as sold in developing country markets.

investigated two locally available and commonly utilized chemical water flocculation methods–alum and moringa flocculation–in laboratory-controlled circumstances, to determine whether use of these mechanisms reduced turbidity and chlorine demand before chlorination. Reduction of turbidity would cause a visual improvement in the treated water that could help encourage correct and consistent use among SWS users. Reduction of chlorine demand would allow the use of a lower dosage of sodium hypochlorite, which could increase acceptability and reduce the cost of treatment.

Aluminium sulfate is the most widely used flocculant in United States water treatment facilities (AWWA 1999). Unrefined alum is sold inexpensively in developing country markets as a naturally occurring mineral block of soft white stone (Figure 1). This product is used for household flocculation by: 1) crushing it into a powder, adding it to water, stirring, settling and decanting supernatant water; or 2) stirring the whole stone in water for a few seconds and waiting for solids to settle. The promotion of alum for household flocculation is inhibited because: 1) the quality of alum varies unpredictably; 2) there is no established correct or simple dosage mechanism for alum; and 3) overdosage causes a salty, unpalatable taste.

The moringa tree (*Moringa oleifera*) is native to north-western India, grows throughout the tropics, and contains a natural polyelectrolyte with flocculation properties. To use moringa for household flocculation, seeds are removed from the dried pods, shelled, and crushed using a mortar and pestle (Figure 2). The powder, or a tincture of the powder in water sieved through a cloth, is added to household water, stirred, settled and decanted. Moringa has been shown to be effective at reducing turbidity by 80–99.5% and microbiological contamination by 90–99.99% in water at a dose of 200 $\mathrm{mg\,l^{-1}}$ (approximately one seed per litre) (Madsen *et al.* 1987). Some NGOs, such as Trees for Life (www.treesforlife.org/), recommend moringa tree

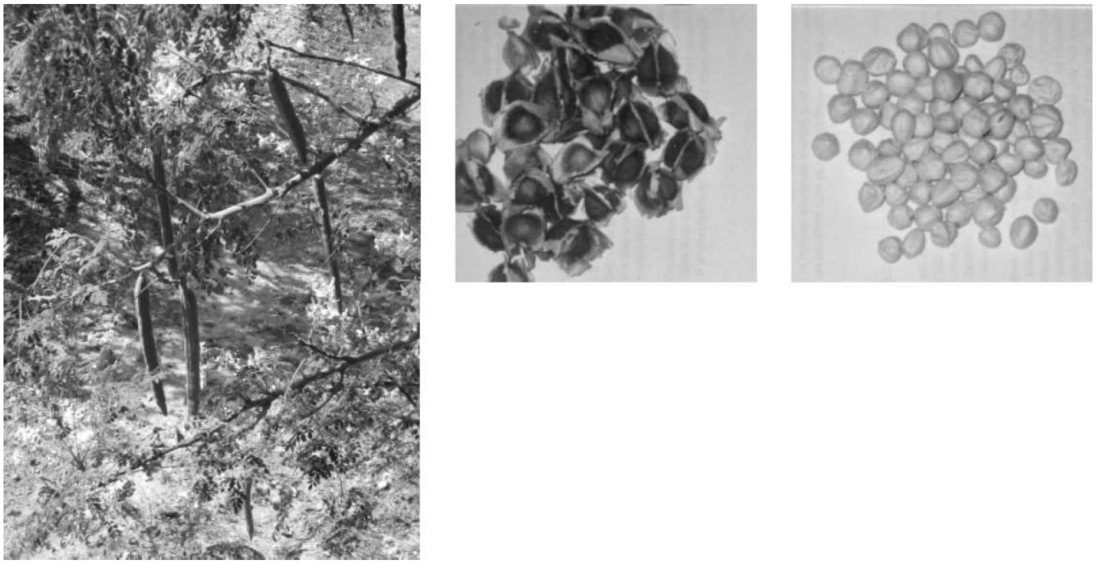

Figure 2 | Moringa tree with pods (left panel); moringa seeds (middle panel); shelled moringa seeds (right panel).

growth and promotion to eradicate world hunger, generate biodiesel, and treat illnesses and drinking water. To treat water, Trees for Life recommends adding 50–150 mg l^{-1} of ground moringa seeds dissolved in clean water and sieved through a strainer and cloth. Water is then stirred quickly for 30 seconds, slowly stirred for five minutes, and settled for one hour before decanting and drinking. Promotion of moringa for household flocculation has been inhibited because: 1) quality of moringa varies unpredictably; 2) flocculation efficiency is dependent on initial turbidity and moringa storage conditions (Katayon *et al.* 2006); and 3) the procedure is time consuming.

METHODS

Setting

This research was conducted in the laboratories of the Department of Civil and Environmental Engineering at Lehigh University in Bethlehem, Pennsylvania.

Study design

We analysed turbidity and chlorine demand reduction compared with controls using alum and moringa flocculation before chlorination with a 1.875 and 3.75 mg l^{-1} sodium hypochlorite dose in waters with turbidity of 10, 30, 70, 100 and 300 NTU (Table 1).

Turbid waters were created synthetically in the laboratory using surface water and bottom sediments collected from Saucon Creek, Bethlehem, Pennsylvania, diluted with laboratory-grade water (i.e., tap water filtered through RiOs and Milli-Q Biocel ultrapure water systems (Millipore Corporation, Billerica, Massachusetts). Turbidity was measured in triplicate using a Hach 2100P portable turbidimeter (Chestertown, Maryland). Chlorine was added to the water in the form of a 1.25% sodium hypochlorite solution prepared monthly using Clorox® bleach diluted with laboratory-grade water and stabilized to a pH above 11.9 with 0.5 M sodium hydroxide. Sodium hypochlorite solution was stored in a capped, opaque plastic bottle at 25°C. Sodium hypochlorite solution concentration was verified prior to each use with Hach (Loveland, Colorado) Iodimetric Titration Method 8209 for high-range total chlorine.

Table 1 | Study design for alum and moringa coagulation*

Turbidity	Bucket number	Clarified	Sodium hypochlorite dosage (mg l^{-1})
10	1	Control	1.875
	2	Settled/decanted	1.875
	3	Clarified	1.875
	4	Clarified	3.75
30	5	Control	1.875
	6	Settled/decanted	1.875
	7	Clarified	1.875
	8	Clarified	3.75
70	9	Control	1.875
	10	Settled/decanted	1.875
	11	Clarified	1.875
	12	Clarified	3.75
100	13	Control	1.875
	14	Settled/decanted	1.875
	15	Clarified	1.875
	16	Clarified	3.75
300	17	Control	1.875
	18	Settled/decanted	1.875
	19	Clarified	1.875
	20	Clarified	3.75

*Buckets 2, 6, 10, 14 and 18 were omitted for moringa testing because of laboratory constraints.

Before initiating alum testing, an appropriate alum dosage regime was developed. Efficacy testing of alum dosages from 0.05 to 1.0 mg l^{-1} at removing turbidity in waters with turbidities of 10, 30, 70, 100 and 300 NTU was conducted. Based on this data (presented in the results section) an alum dosing regime was selected.

For alum tests, 20 turbid water buckets (four each at 10, 30, 70, 100 and 300 NTU) were prepared (Table 1). One bucket at each turbidity with 10 litres of water was treated with a single sodium hypochlorite dose (1.875 mg l^{-1}) as a control, and the remaining three buckets for each turbidity, each with 15 litres of water, were: 1) settled and decanted for two hours only and treated with a single dose of sodium hypochlorite; 2) treated with alum, settled and decanted, and treated with 1.875 mg l^{-1} of sodium hypochlorite; or 3) treated with alum, settled and decanted, and treated with 3.75 mg l^{-1} of sodium hypochlorite.

Alum blocks purchased in the Kisumu market, Kenya, were crushed with a hammer and ground into fine powder using a mortar and pestle. Alum treatment consisted of stirring the appropriate dosage of alum powder into water for 3 minutes with a plastic spoon before letting water settle for 2 hours. After settling, 10 litres of supernatant water from the alum-treated and settled and decanted control buckets were decanted to clean buckets. Care was taken to prevent resuspension of settled solids during decanting.

For moringa testing, 15 turbid water buckets (three each at 10, 30, 70, 100 and 300 NTU) were prepared (Table 1). One bucket at each turbidity with 10 litres of water was treated with a single dose (1.875 mg l^{-1}) of sodium hypochlorite as a control, and the remaining two buckets, each with 15 litres of water, were: 1) treated with moringa, settled and decanted, and treated with a 1.875 mg l^{-1} dose of sodium hypochlorite; or, 2) treated with moringa, settled and decanted, and treated with a 3.75 mg l^{-1} dose of sodium hypochlorite.

Moringa tests were performed at each turbidity level with two moringa doses: 100 mg l^{-1} and 200 mg l^{-1}, equivalent to approximately half a seed and one seed per litre, respectively. These dosages are consistent with prior research and NGO recommendations (Madsen *et al.* 1987; www.treesforlife.org/). Dried moringa seeds (ECHO Inc., North Fort Myers, Florida) were shelled and crushed into powder using a mortar and pestle. The appropriate amount of powder for treating one bucket was added to 150 ml of laboratory-grade water in a screw-capped glass bottle and shaken vigorously for 1 minute, settled for 10 minutes, and filtered through VWR 40 μm filter qualitative crepe 417 filter paper (West Chester, Pennsylvania). The filtrate was stirred into the turbid water with a plastic spoon vigorously for 2 minutes and slowly for 5 minutes, and water was settled for 2 hours. After settling, 10 litres of water from the moringa-treated buckets were decanted to clean buckets. Care was taken to prevent resuspension of settled solids during decanting.

Free chlorine residuals were measured in all buckets 1, 2, 4, 8 and 24 hours after chlorination using a Hach DR/4000 U spectrophotometer and DPD-1 free chlorine reagent (method 8021). Testing was discontinued if free chlorine residual degraded to 0 mg l^{-1} within 24 hours.

Data analysis

Data were analysed using the Analysis ToolPak in Microsoft Excel and SAS version 9.1 (SAS Institute, Cary, North Carolina). Free chlorine residuals in treated and untreated waters at each time at each turbidity were compared using the *t*-test.

RESULTS

Alum dosage testing

Before initiating alum testing, alum dosage testing at 10, 30, 70, 100 and 300 NTU was conducted, with settling and decanting controls (Table 2). Settling and decanting alone reduced turbidity by 24.5–68.3% at turbidities 10–300 NTU. At 10 and 30 NTU, alum was less effective than settling and decanting at reducing turbidity. Increasing dosages were increasingly less effective. At 70, 100, and

Table 2 | Percentage turbidity reduction from (i) settling and decanting controls and (ii) alum doses from 0.05 to 1.0 mg l^{-1} compared with settling and decanting controls

Initial turbidity (NTU)	10	30	70	100	300
Settling and decanting control*	24.5% (19.3–29.7)	51.0% (43.0–59.0)	55.5% (45.6–65.5)	52.1% (42.3–61.9)	68.3% (65.4–71.3)
Alum dose (mg l^{-1})	**% reduction compared with settling and decanting control (95% confidence intervals)**				
0.05	−4.0 (−11.5–3.5)	4.1 (1.3–6.9)	11.5 (3.8–19.2)	17.4 (9.6–25.2)	27.7 (24.4–31.1)
0.25	−42.6 (−55.9– −29.3)	4.2 (−17.8–26.3)	15.2 (5.1–25.4)	19.1 (2.7–35.4)	25.6 (23.5–27.8)
0.5	−59.4 (−95.0– −23.9)	−8.4 (−23.8–7.0)	13.7 (4.6–22.8)	23.7 (16.4–31.1)	26.4 (23.2–29.6)
1.0	−16.4 (−32.0– −0.8)	−14.8 (−26.4– −3.1)	17.2 (7.8–26.5)	28.4 (19.7–37.2)	25.9 (23.5–28.3)

*Values are average percentage turbidity reduction (with 95% confidence intervals).

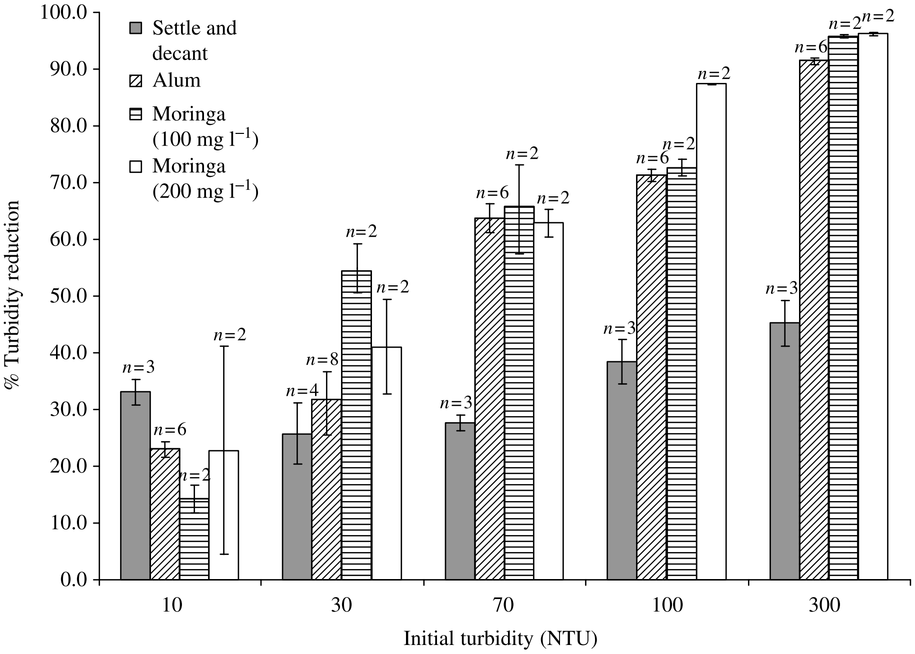

Figure 3 | Average turbidity reduction after settling and decanting, alum flocculation and moringa flocculation (error bars represent standard error of the mean; *n* values indicated).

300 NTU, alum was more effective than settling & decanting at reducing turbidity, with increased dosing improving efficacy slightly at 70 and 100 NTU. Based on these data, and in consideration of the need for a clear and simple dosing regime, a 0.05 g l^{-1} dose of alum powder was used for water with initial turbidities of 10 and 30 NTU, and a 1 g l^{-1} dose was used for water with initial turbidities of 70, 100 and 300 NTU.

Turbidity reduction

All turbidity samples were conducted in triplicate to ensure accuracy, and averaged for reporting purposes. The average percentage error of the triplicate samples was 1.4%, with a minimum of 0.0%, a maximum of 10.6%, and a standard deviation of 1.4% of the goal turbidities of 10, 30, 70, 100 and 300 NTU. The actual laboratory initial turbidity values were, on average, within 3.1% of the goal turbidities of 10, 30, 70, 100 and 300 NTU. The minimum error from intended initial turbidity was 0.0%, the maximum error was 17.0%, and the standard deviation was 3.8%.

Settling and decanting alone resulted in relatively consistent turbidity reductions of 25.7–45.3% across all initial turbidities (Figure 3). After alum flocculation, turbidity was reduced from a minimum of 23.0% at initial turbidity of 10 NTU to a maximum of 91.4% at initial turbidity of 300 NTU. After moringa flocculation, turbidity was reduced from a minimum of 14.2% and 22.8% at initial turbidity of 10 NTU at doses of 100 mg l^{-1} and 200 mg l^{-1}, respectively, to a maximum of 95.9% and 96.2% for the two doses at initial turbidity of 300 NTU. As can be seen in the figure, the effectiveness of the coagulants at reducing turbidity increased with turbidity. At 10 NTU, the use of alum and the 100 mg l^{-1} moringa dosage statistically significantly reduced turbidity compared with settling and decanting controls ($p = 0.0004$ and $p = 0.01$, respectively). At 30 NTU, only the 100 mg l^{-1} moringa dose statistically significantly reduced turbidity compared with settling and decanting controls ($p = 0.03$). At 70, 100 and 300 NTU, the use of alum and both moringa doses (100 mg l^{-1} and 200 mg l^{-1}) statistically significantly reduced turbidity compared with settling and decanting controls ($p < 0.01$).

Chlorine demand reduction

Free chlorine residual was monitored for 24 hours after sodium hypochlorite addition in each bucket. A representative example result, depicting free chlorine decay over

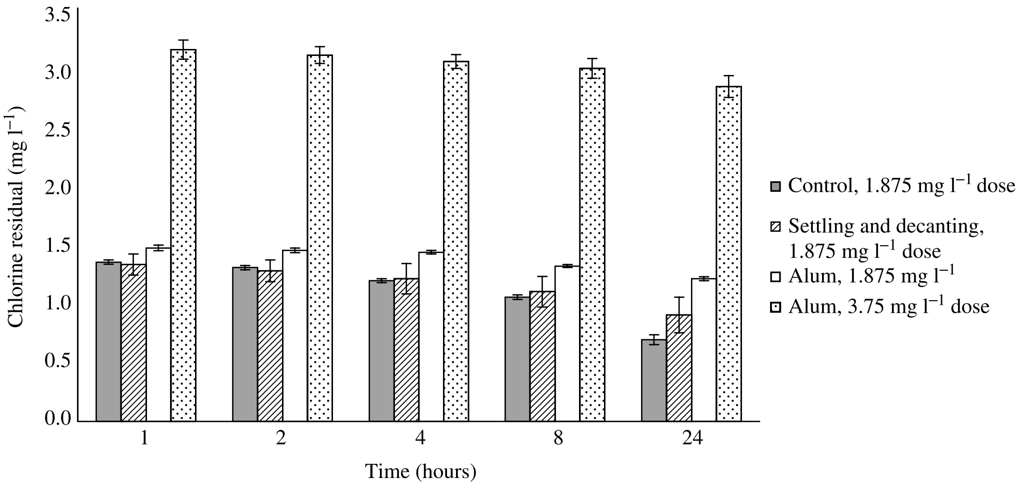

Figure 4 | Chlorine decay over time in waters treated with 1.875 and 3.75 mg l^{-1} doses of chlorine (initial turbidity = 100 NTU); error bars represent the standard error of the mean ($n = 3$).

time at 100 NTU initial turbidity in: 1) the 1.875 mg l^{-1} sodium hypochlorite dose control; 2) the 1.875 mg l^{-1} dose settling and decanting control; and 3) the 1.875 mg l^{-1} and 3.75 mg l^{-1} dose after alum flocculation, is displayed in Figure 4. As can be seen, free chlorine residuals in the control, settled and decanted, and alum-flocculated water decayed over time. Figure 4 is consistent with results seen in all alum tests.

At all initial turbidities, alum-flocculated waters maintained higher free chlorine residual at 24 hours than chlorination-only and settling and decanting controls (Figure 5). The free chlorine residual difference between alum-flocculated and control waters ranged from 0.05 mg l^{-1} (10 NTU) to 0.64 mg l^{-1} (70 NTU), and between alum-flocculated and settled and decanted controls ranged from 0.19 mg l^{-1} (10 NTU) to 0.57 mg l^{-1} (70 NTU). This free chlorine residual difference between control and alum-flocculated waters was significant using the *t*-test 24 hours after chlorine addition at 30 NTU ($p = 0.05$), 70 NTU ($p = 0.06$), 100 NTU (0.01) and 300 NTU ($p = 0.02$), but not at 10 NTU ($p = 0.87$). Alum flocculation was more effective at maintaining free chlorine residual than settling and decanting at 30 NTU ($p = 0.04$), 70 NTU ($p = 0.07$), and 300 NTU ($p = 0.09$), but not at 10 NTU ($p = 0.25$) or

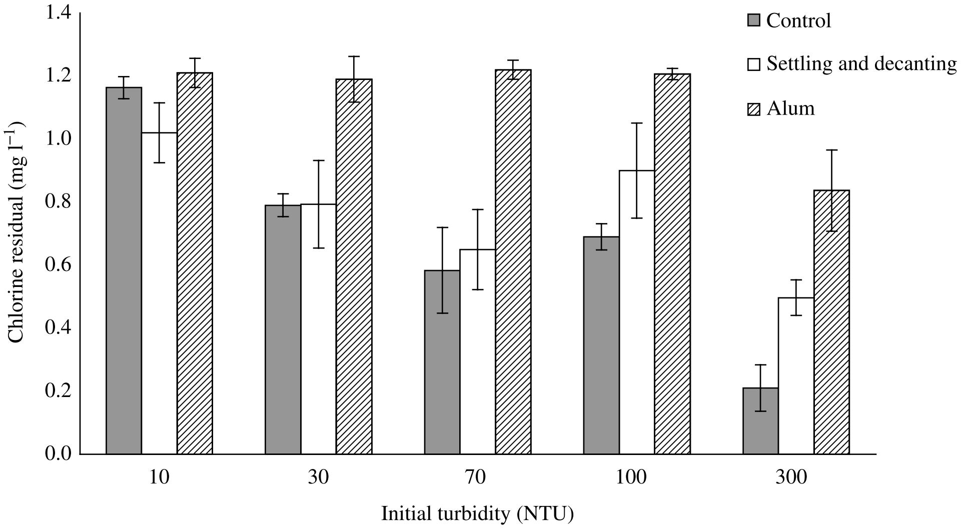

Figure 5 | Chlorine residual at 24 hours for waters treated with a 1.875 mg l^{-1} dose of chlorine; error bars represent standard error of the mean ($n = 3$).

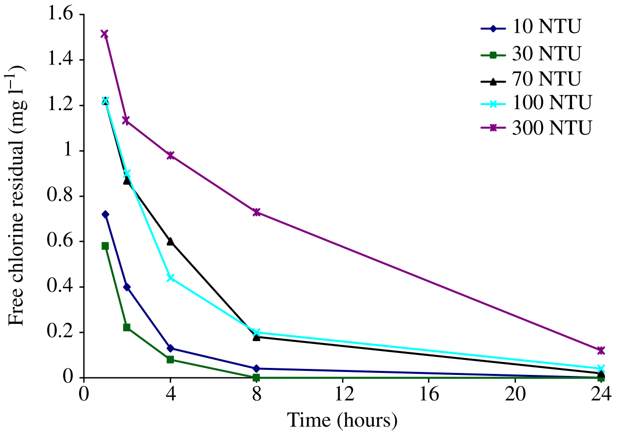

Figure 6 | Chlorine residual over time for waters treated with 100 mg l^{-1} dose moringa flocculation followed by 3.75 mg l^{-1} sodium hypochlorite dose.

100 NTU ($p = 0.17$). Settling and decanting was only more effective than chlorination-only controls at maintaining free chlorine residual at 300 NTU ($p = 0.01$ at 24 hours after chlorine addition).

All moringa-flocculated samples had lower free chlorine residual at 24 hours than chlorination-only controls. For 100 and 200 mg l^{-1} moringa doses at all initial turbidities, water treated with a 1.875 mg l^{-1} dose of sodium hypochlorite decayed to 0 mg l^{-1} residual in less than 24 hours. Water treated with 100 mg l^{-1} moringa and a 3.75 mg l^{-1} sodium hypochlorite dose had slight free chlorine residuals at 24 hours at initial turbidities of 70, 100 and 300 NTU (Figure 6). However, these residuals were below the 0.2 mg l^{-1} SWS minimum objective. Water treated with 200 mg l^{-1} moringa and a 3.75 mg l^{-1} dose of chlorine decayed to 0 mg l^{-1} residual 24 hours after treatment at all initial turbidities (Figure 7). As can be seen in Figures 6 and 7, higher free chlorine residual levels were maintained in waters with higher initial turbidity.

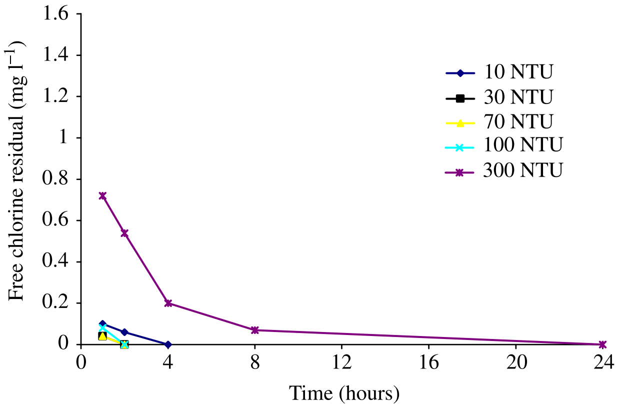

Figure 7 | Chlorine residual decay over time for waters treated with 200 mg l^{-1} dose moringa flocculation followed by 3.75 mg l^{-1} sodium hypochlorite dose. Note: 30 NTU and 70 NTU data overlap.

DISCUSSION

Both alum and moringa flocculation effectively reduced turbidity, with a trend of increased percentage reduction at higher initial turbidities. These results indicate that both treatments are appropriate in areas with high turbidity, and are consistent with previous research (Madsen *et al.* 1987) and standard practice (AWWA 1999). A dosage of 1 g l^{-1} of alum was established for waters with turbidity ≥ 70 NTU, which is consistent with established practices for aluminium sulfate (AWWA 1999).

As expected because of its wide usage in water treatment facilities, alum flocculation was an effective mechanism to reduce turbidity and chlorine demand. Alum-flocculated waters at all initial turbidities treated with a 1.875 mg l^{-1} sodium hypochlorite dose met SWS free chlorine residual objectives. Alum-flocculated waters at all initial turbidities treated with a 3.75 mg l^{-1} sodium hypochlorite dose had free chlorine residuals >2.0 mg l^{-1} after 24 hours, exceeding the SWS recommended maximum of 2.0 mg l^{-1}. In addition, all settled and decanted waters and chlorination-only controls (except at 300 NTU) treated with a 1.875 mg l^{-1} sodium hypochlorite dose met SWS free chlorine residual objectives. Although the alum-treated, settled and decanted, and control water (with the exception of 300 NTU) all met the SWS objectives for 24-hour free chlorine residual, the residual in alum-treated waters was higher. Alum treatment for waters ≥ 30 NTU is recommended for optimum water quality, although even turbid water will likely be safe to drink 24 hours after a 1.875 mg l^{-1} sodium hypochlorite dose as long as settling and decanting occurs before chlorination.

In this study, the settling and decanting controls were effective at reducing turbidity and chlorine demand compared with chlorination-only controls at 300 NTU. However, other investigations have documented greater efficacy of settling and decanting alone as a pretreatment mechanism that significantly reduces turbidity and chlorine demand (Kotlarz *et al.* 2009). The difference between the two studies is that water was settled for 24 hours in the settling and decanting efficacy study, while settling occurred for only 2 hours in this study. This disparity in efficacy highlights the need to recommend a longer than 2-hour settling time in order for settling and decanting to be fully effective.

Rather than reduce chlorine demand as potentially expected, moringa flocculation increased chlorine demand to the point where adequate free chlorine residual was not maintained for 24 hours after treatment. Increased moringa doses further increased chlorine demand. It should be noted that waters treated with 100 $mg\,l^{-1}$ moringa and 3.75 $mg\,l^{-1}$ sodium hypochlorite maintained adequate free chlorine residuals 2 hours after treatment at 10, 30, 70, 100 and 300 NTU (Figure 6). Therefore, treatment with 100 $mg\,l^{-1}$ moringa and 3.75 $mg\,l^{-1}$ sodium hypochlorite could be an appropriate water treatment option if water is immediately consumed within 2 hours of treatment (i.e., to eliminate the opportunity for recontamination in storage); however, the volumes of water treated with moringa (i.e. 10–20 l) are not likely to be consumed in their entirety within 2 hours, making water treatment with moringa and chlorine an unrealistic recommendation in developing country circumstances.

As both the 100 $mg\,l^{-1}$ and 200 $mg\,l^{-1}$ moringa dose similarly reduced turbidity, it is possible that lowering the moringa dose may still reduce the turbidity without increasing the chlorine demand beyond the ability to maintain 0.2 $mg\,l^{-1}$ free chlorine residual 24 hours after treatment. However, lowering the moringa dose is contrary to existing research on moringa efficacy and recommendations for moringa dosage, and unlikely given the high chlorine demand observed (Madsen *et al.* 1987; www.treesforlife.org/). Interestingly, chlorine demand decreased as initial turbidity increased with both moringa doses. This could be because at higher turbidities the organic material in the moringa binds to the organic turbidity-causing material, preventing the moringa organic material from exerting as large a chlorine demand as at the lower turbidities.

These moringa results are not unexpected based on the literature. A method to extract the coagulant protein from moringa using a single-step batch ion exchange method has been optimized so that moringa can be used in water treatment plants and industry, without ‘release [of] organic and nutrient loads to the water, which are the main concerns of the crude extract’ (Ghebremichael *et al.* 2006; Bhuptawat *et al.* 2007). In addition, higher trihalomethane (THM) levels have been identified in moringa-flocculated waters compared with controls (Lantagne *et al.* 2008), indicating the presence of additional organic material that increases chlorine demand and THM formation potential.

Recommendations for organizations implementing SWS programmes in areas with highly turbid waters are discussed elsewhere (Kotlarz *et al.* 2009). The four options discussed included: 1) no pretreatment (i.e. direct chlorination of turbid water with a double dose (3.75 $mg\,l^{-1}$) of hypochlorite solution); 2) pretreatment of turbid water with a physical clarification mechanism, such as cloth filtration, settling/decanting, sand filtration, or a combination of the above before chlorination; 3) pretreatment of turbid water with a chemical coagulation step, such as alum or moringa before chlorination; and 4) treatment of turbid water with an alternative household water treatment product, such as a ceramic or biosand filter, or the Procter & Gamble flocculent-disinfectant product PuR™. Each of these options has benefits and drawbacks, and the factors that influence a sponsoring organization’s recommendation might include: 1) the cost of treatment; 2) local availability; and 3) acceptability of the option to the users and the organization.

The added value of this research for the above discussion is threefold: 1) using raw moringa seeds for pretreatment before chlorination is no longer recommended; 2) a 24-hour settling time is recommended for settling and decanting to be fully effective at reducing turbidity and chlorine demand; and 3) a pilot project investigating the efficacy and acceptability in real-world circumstances of distributing, or selling, pre-ground, pre-dosed small plastic bags of alum to use before chlorination is indicated. If the pilot project is successful, distribution of this ‘ready-to-use’ alum for flocculation could develop into a micro-enterprise.

Further research is indicated to: 1) determine acceptability of using alum flocculation before chlorination in real-world circumstances; and 2) quantify the potential reduction of THM formation potential when alum flocculation is used before chlorination. Lastly, because of inherent variability in local formulations of alum, moringa and turbidity sources, our results may hold only for the specific formulations and turbidity sources used here. These results warrant replication in other turbid source waters using different formulations of alum and moringa for water treatment.

CONCLUSIONS

Implementation of SWS programmes in areas with turbid water has been complicated by unanswered questions regarding correct sodium hypochlorite dosage and user acceptability. Two locally available chemical pretreatment mechanisms, alum and moringa flocculation, were found to be effective at reducing turbidity in waters ≥ 70 NTU. Treatment with alum reduced chlorine demand in waters ≥ 30 NTU, leading to significantly higher free chlorine residuals in stored water 24 hours after treatment. Treatment with moringa, however, increased chlorine demand compared with controls at all turbidity levels. Moringa flocculation is not recommended as a pretreatment mechanism before chlorination. Pretreatment with alum is recommended for source waters with turbidity ≥ 30 NTU to improve the effectiveness, reduce the cost and increase the acceptability of water treatment with sodium hypochlorite at the point of use.

ACKNOWLEDGEMENTS

This work was partially supported by a National Science Foundation CAREER grant to co-author Jellison (award #0545687).

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First received 18 January 2009; accepted in revised form 13 April 2009. Available online 9 November 2009