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Research Paper

Treatment of drinking water for rural households using *Moringa* seed and solar disinfection

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ABSTRACT

Rural populations in Tanzania use unsafe drinking water from unimproved water sources which are inadequately treated using plant seed powder. The effectiveness of defatted crude seed extract (dCSE) of *Moringa oleifera* along with water filtration and solar disinfection (SODIS) for rural household water treatment was investigated. The performance of dCSE in turbidity and bacteria reduction was evaluated in 20 L buckets using river water with varied turbidities. Coagulation–flocculation processes were conducted using different dosages of 5% (Weight/Volume) dCSE. Optimum dosage for maximum turbid removal was established after 2–6 h of settling time. Optimum dosages of dCSE were 20, 30 and 80 mL/20 L for water with a turbidity of 150, 450 and 1,000 NTU with turbidity removal efficiencies of 98, 99 and 99%, respectively. The filtration process was able to remove about 66% of suspended solids from pretreated water by dCSE after coagulation/flocculation/sedimentation. SODIS of pretreated water in black painted and unpainted bottles removed 99 and 97.6%; 99.9 and 98.6% of total and fecal coliforms after 6 h of sunlight exposure, respectively. The pH and color of treated water were within Tanzania Standards. This study recommends dCSE, filtration and SODIS for use at household level for water treatment and storage using pots.

Key words | *Moringa* seed protein, rural women, Tanzania, turbid water, water purification

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HIGHLIGHTS

- The defatted crude seed extract (dCSE) can be used for turbid water treatment in Tanzania.
- The elevated solar radiation and temperature between 12 noon and 3 p.m. disinfect water clarified by dCSE for drinking in rural communities.
- The developed water treatment technology can directly apply at household level with limited formal technical knowledge.

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INTRODUCTION

Most rural communities especially in developing countries lack access to safe drinking water, and globally, at least 2 billion people use contaminated drinking water sources (WHO 2019). This situation has resulted in health hazards, especially the transmission of diseases such as diarrhea, cholera, dysentery, typhoid and polio which cause considerable mortality (WHO 2019). The Sustainable Development Goal (SDG) 6 of the United Nations emphases availability of water as well as sustainable management of water and sanitation. Moreover, two sub-goals/targets, namely targets 6.1 and 6.3 are focusing on access to safe and affordable drinking water by all by 2030 and improving water quality, respectively. Nevertheless, in the course of the development of the post-2015 goals, it was revealed that there are still remarkable challenges towards achieving the SDGs goals, particularly in remote rural settings (United Nations 2015).

Conventional drinking water treatment comprises coagulation, flocculation, sedimentation, filtration and disinfection processes (Abiyu *et al.* 2018). Purification of potable water from turbid surface water sources by coagulation–flocculation and sedimentation processes for the removal of suspended and colloidal materials is common in both the water supply industry and household-scale water treatment in many rural areas of Tanzania where improved water supply services are scarce. Aluminum salts are the common chemical coagulant used in the water industries worldwide although several studies have reported shortcomings of these chemicals including increased turbidity due to the formation of aluminum precipitates and human health like Alzheimer's disease (Tomljenovic 2011; Kimura *et al.* 2013). On the other hand, most developing countries cannot procure adequate water treatment chemicals due to high costs associated with importing such chemicals (Wilson & Andrews 2011).

In Tanzania, 69% of the population are directly served with water in the national and regional areas (EWURA 2020a) while in district and township, up to 62% of the population is directly served with water (EWURA 2020b). This condition suggests that water supply and quality in rural areas is still a challenge in Tanzania as reported by previous researchers (Marobhe 2008; ADB 2010) that the water supply coverage is less than 61.5%. Thus, large populations in rural areas rely on heavily polluted sources including rivers, small dams, ponds and traditional wells. Rural women and girls especially in central parts of Tanzania, who are responsible for water drudgery, treat drinking water for their families using seed powder as natural coagulants. Among the plants which produce seeds used for water coagulation include *Moringa oleifera* (MO), *Parkinsonia aculeata, Voandzea subterranea, Bombaxceiba* and a variety of seeds from leguminous plants. However, women lack technological guidance on proper water treatment procedure using seed powder, and hence, they seldom get good water clarification results. In recent years, there has been a growing interest in MO seed as a natural coagulant. MO belongs to the Moringaceae family and is widely spread throughout tropical countries. It is a nontoxic and drought tolerant tree which possesses medicinal and nutritional properties, including water-purification properties (Hellsing *et al.* 2014). The use of MO seed as a natural coagulant in rural areas of Tanzania and other developing countries will provide people additional benefits from the extraction of useful products from the seed powder. These include edible and other useful oils, residual solids which may be used as animal feed and fertilizer and seed backs for briquette production.

Solar disinfection (SODIS) applications have great potential for the reduction of pathogenic organisms in drinking water (Conroy *et al.* 2001). The synergistic effect of UV light and temperature during SODIS of microbiologically contaminated water has been reported to be effective for water with low turbidity and color (Wilson & Andrews 2011). The SODIS method is greatly reliant on the UV transparency of the bottle materials. Polyethylene terephthalate (PET) bottles have been one of the most preferred plastic materials for SODIS because they are easily accessible, reasonably UV-A-transparent, chemically stable, lightweight and durable (Carey *et al.* 2011). This study will also apply the SODIS technique to inactivate residual bacteria in the water pretreated using MO crude seed extract so as to reduce turbidity. This is because it is difficult to destroy microbial contaminants in high turbid waters due to the shielding effect of suspended particles. The main objective of the present work is to investigate the potential of defatted MO crude seed extract and water filtration on the removal of suspended particles (turbidity) and SODIS on the removal of residual bacteria in the water pretreated using seed extract. All investigations were performed under varied operating factors that affect the coagulation and bacteria disinfection process. All these together lead to a better understanding of the performance of coagulation and disinfection processes and hence establish its usefulness for water treatment at rural household level.

MATERIALS AND METHODS

Source of water samples and sampling procedure for coagulation

This is an experimental research (Kothari 2004) that applied principles of water purification at household level. Materials used included the raw water which obtained from Ruvu River. The Ruvu River is used as a boundary between Kibaha and Chalinze districts, in the coastal region. The sampling point is located about 200 m upstream of the Upper Ruvu River Intake and about 65 km west of Dar es Salaam commercial city with coordinates of Latitude: $-6°49'24.56''$ S and Longitude: $39°16'10.24''$ E. The Ruvu River is also the main source of water for more than 6 million people in Dar es Salaam city and some part of the coastal region particularly Kibaha, Kisarawe and Bagamoyo districts. Communities which are situated nearby the Ruvu River banks who lack piped water supply services use the river for drinking and other domestic activities. The sampling point was accessed through access footpaths which are used by local people to encroach the river for different activities including fetching water.

A grab technique was used to sample water at the top level of flowing water and at a certain depth below the water surface so as to obtain water with different turbidities. All water samples were collected aseptically in clean, sun-dried 20 L buckets and transported to the biotechnology laboratory at Ardhi University, Dar es Salaam, Tanzania. Water samples with 250 NTU (moderate turbidity), 500 NTU (high turbidity) and 1,000 NTU (very high) levels were prepared in the laboratory by mixing water samples collected from different depths and used for coagulation–flocculation experiments to remove turbidity and reduction of intestinal pathogen indicators. These turbidities were chosen because they are within the range of turbidities that are commonly encountered in Ruvu River during different seasons of the year.

Preparation of *Moringa* defatted crude seed extract

Dry MO seeds were purchased from the Kariakoo market in Dar es Salaam. The seed coats were removed, and the seed kernels were ground into fine powder using mortar and pestle. The seed powder was defatted by spreading it on the surface of adsorbent paper sheets and exposed to the sunlight for a period of 8 h for two consecutive days until the oil separated from the seed powder and absorbed into absorbent sheets. The defatted seed powder was ground again and sieved using a fine plastic tea strainer with pore size of approximately 0.3–0.5 mm. Rural women use special granite stones to grind seeds into very fine powder.

Defatted crude seed extract (dCSE) (5% W/V) was prepared by suspending 5 g of the defatted MO seed powder in 100 mL of distilled water followed by stirring for 15 min at room temperature (27 ± 2 °C) using a magnetic stirrer so as to extract coagulating proteins. The suspension was filtered through a special nylon material, and the filtrate termed dCSE was used as a natural coagulant in coagulation–flocculation experiments. Several trials varying from 3 to 6% (W/V) of dCSE were done on coagulation activity before the verdict to use 5% dCSE for the study was reached. The choice of the dCSE percent solution for use in testing the coagulation activity (i.e. 5% W/V) was based on the practicality and consistency in dosages (mL/20 L) used in coagulation of water with different turbidities. The use of too low or too high percentage dCSE solution necessitated using very high volumes or too low volumes, respectively, which were observed to be impractical.

Characteristics of raw water and dCSE

Physical, chemical and biological parameters of Ruvu River water samples were analyzed to understand their quality characteristics. Similarly, dCSE was also analyzed to determine its composition to check if there is any parameter which could have an influence on the coagulation process. All analytical methods followed the Standard Methods of Water and Wastewater Examinations (APHA/AWWA/WEF 1998). Color, turbidity, nitrate-N, nitrite-N, manganese, ammonia–nitrogen and iron were analyzed spectrophotometrically using a spectrophotometer (model DR/4000U). In addition, alkalinity, calcium, total hardness and chloride were analyzed by titration using the digital titration unit (HACH SENSION 156) with respective chemical reagents as detailed in APHA/AWWA/WEF (1998). The water pH, TDS, conductivity and salinity were analyzed using the electrode meter (model HQ 40D).

Coagulation–flocculation of turbid water and filtration

Four buckets with equal capacity were filled with 20 L of Ruvu River water with different turbidities in which different dosages of dCSE were added as follows: 20–80 mL were added in water with medium (150 NTU) and high (450 NTU) turbidity while 70–200 mL were added in water with very high turbidity (1,000 NTU). Thereafter, the water was rapidly mixed (about 90 rpm) for 1–2 min to disperse the dCSE coagulant using a special wooden spoon (with the dimension of 635 mm long × 85 mm width) followed by slow mixing for the flocculation process and finally settlement stage (Figure 1). Rapid mixing speed was maintained more or less constant by making counts in Swahili language (i.e. *moja* (1), *mbili* (2), *tatu* (3), *nne* (4) up to 50 (*hamsini*)) which correspond to the number of times the wooden spoon is rapidly rotated in the water. In this case, the counting up to 50 at an established consistent counting speed represented 90 rpm.

Two different techniques were tried for the slow mixing process. The first one involved slow mixing at about 10 rpm for 15 min soon after the end of rapid mixing. The second technique was to allow the water to swirl itself after rapid mixing with the mixing spoon removed from the water until the water stops swirling and stands still. Out of these two slow mixing techniques, the second one was found to be very effective and the time taken for water to flocculate ranged between 25 and 30 min. The main drawback of using a wooden spoon for slow mixing is based on the fact that flocs which are formed tend to break down very easily if the mixing speed is slightly altered. Thus, at the end of the flocculation procedure, the water was allowed to settle undisturbed for about 1–8 h. Thereafter, about 50 mL of the clarified water samples were collected about 5 cm from the surface of the settled water and the residual turbidities were measured as described before. Minimum dosage which produced the highest turbidity removal was considered the optimum dosage for that particular turbidity level. Other water quality parameters namely color and pH were also analyzed in the filtered water.

The treated water samples with the lowest turbidities at optimum dosages of dCSE and settling time were filtered using a clean muslin cloth for further reduction of suspended particles.

Figure 1 | (a) Rapid mixing after coagulation with different dosages of dCSE (coagulation process), (b) slow self-water mixing (flocculation processes) and (c) treated water during the settling process.

Preparation of PET bottles for SODIS studies

Empty PET drinking water bottles with a capacity of 1.5 L were collected from the nearby cafeterias and used for SODIS studies of the pre-clarified water using dCSE and filtration. The PET bottles were used in this study because bottled drinking water is widely used in urban and peri-urban areas of Tanzania, and hence empty PET bottles are free of charge and also easily accessible. Before being used in SODIS experiments, the PET bottles with covers were thoroughly rinsed three times with tap water. Thereafter, dry bottles were soaked in 1% lime crystals solution (pH 2.3–2.5) overnight for disinfection purposes. Then, the bottles were rinsed three times with sterile distilled water before being used in SODIS experiments.

SODIS experimental setup

All solar experiments were conducted on cloudless days on 13 and 22 February 2019 in Dar es Salaam. Solar irradiance studies used turbid water with an initial turbidity of 1,000 NTU after being treated using dCSE and filtration. The clarified water was dispensed in 12 disinfected PET bottles. Six bottles were black painted of which three were half-filled and the other three fully filled. It has been reported by Meera & Ahammed (2008) that black-backed bottles have superior SODIS performance. Similarly, of the remaining six unpainted (transparent) bottles, three were half-filled and three were fully filled. Three bottles system was used because one bottle was removed from the sunlight treatment at an interval of 3 h for a further analytical procedure. This practice reduced the risk of contaminating water samples and also avoided fluctuation in water temperature in the bottles. All PET bottles for SODIS experiments were prepared in duplicate in which one set of bottles was meant for monitoring hourly temperature changes in water bottles exposed to solar radiation for 9 h using a thermometer, PCE – ST1 (model CE-PCE; −40 to 250 °C). The other set of PET bottles was for ascertaining the effectiveness of solar radiation and temperature on the inactivation of indicators of intestinal pathogens (coliforms). In this case, all SODIS test bottles were placed horizontally on aluminum sheets located on an elevated concrete tank surface to enhance the heating mechanisms of refracted rays. Ambient outside temperatures during the experiments ranged from 31 to 33 °C. Moreover, solar irradiance was measured from 8.00 a.m. to 5.00 p.m. on the roof surface where the SODIS experiments were mounted using Iso-Tech (model ISM 410) instrument for two aforementioned days so as to establish the average solar irradiance.

For control experiments, two unpainted and two painted PET bottles were half-filled with pretreated water and placed for 9 h in a closed laboratory cardboard to obstruct penetration of sunlight through the bottles.

Effect of solar radiation on microbiological quality of water

Residual total coliforms (TCs) and thermo-tolerant fecal coliforms (FCs) in PET bottles were determined after subjecting unpainted and painted PET bottles filled with water to SODIS procedure. The residual TCs and FCs were determined after 3 h interval (8.00 a.m. to 11.00 a.m., 11.00 a.m. to 2.00 p.m. and 2.00 to 5.00 p.m.) for a period of 9 h starting from 8.00 a.m. to 5.00 p.m. The residual TCs and FCs were enumerated by membrane filtration using liquid media as detailed in Standard Method 9221E Fecal Coliform Membrane Filter Procedure (APHA/AWWA/WEF 1998).

Statistical analysis

One-way analysis of variance (ANOVA) was carried out in order to determine whether there was a difference in water treatment performance using dCSE for water with different water turbidities. Additionally, the paired t-test was used to check if the differences in water temperature in painted and unpainted PET bottles measured during different hours of the day time were significant.

RESULTS AND DISCUSSION

Water quality of Ruvu River and dCSE composition

The results of the quality of raw Ruvu River water and the composition of dCSE are shown in Table 1. The results show that water turbidity, color, iron, FC and TC of Ruvu River are beyond the allowable Tanzanian drinking water

Table 1 | Average physical, chemical and biological quality of raw water samples and crude seed extracts

Parameter	Unit	Ruvu River water	TBS	WHO STD	dCSE
pH		7.57	6.5–8.5	6.5–8.5	6.29
Conductivity	μs/cm	773	2,000	1,000	1,160
TDS	mg/L	388	2,000	1,000	665
Salinity	0/00	0.4	–	–	0.7
Color	MgPt-Co/L	157	50	5	2,000
Turbidity	NTU	450	30	5	–
Manganese	mg/L	–	–	–	0.075
Iron	mg/L	0.965	0.3	0.3	0.449
NO_3-N	mg/L	2.9	10	30	0.093
Chloride	mg/L	32	250	200	600
Calcium	mg/L	170	250	75	420
TCs	Counts/ 100 mL	9×10^5	0	0	ND
FCs	Counts/ 100 mL	5×10^5	0	0	ND

Note: TBS, Tanzania Bureau of Standards.

quality standards. This indicates that rivers like other surface water sources are not clean and safe for drinking and other domestic uses without prior treatment. The use of unsafe polluted surface waters for various domestic purposes is widespread in many parts of rural and peri-urban areas of Tanzania and other countries in the world like Brazil (Pantoja *et al.* 2015).

Moreover, the results in Table 1 show that the dCSE used for water coagulation has high color concentration (2,000 MgPt-Co/L). The high color concentration is due to the nature of CSE extracts being a heterogeneous mixture of different organic materials which have been observed to be removed during the coagulation–flocculation process induced by coagulant protein in the dCSE (Marobhe 2008). The pH of dCSE is also quite acidic (6.29). The acidic nature behaves like traditional chemical alum (aluminum sulfate) coagulant which is used for coagulation processes since its inception. However, unlike alum, a natural coagulant (dCSE) possesses natural buffering capacity, and hence avoids the use of additive to regulate the pH increase alkalinity (Ghebremichael 2004).

Effectiveness of dCSE in turbidity removal

The results on efficacy of varied dosages of dCSE in coagulation–flocculation of water with different initial turbidities and settling time of treated water are presented in Figure 2(a)–2(c). It was revealed that minimum residual

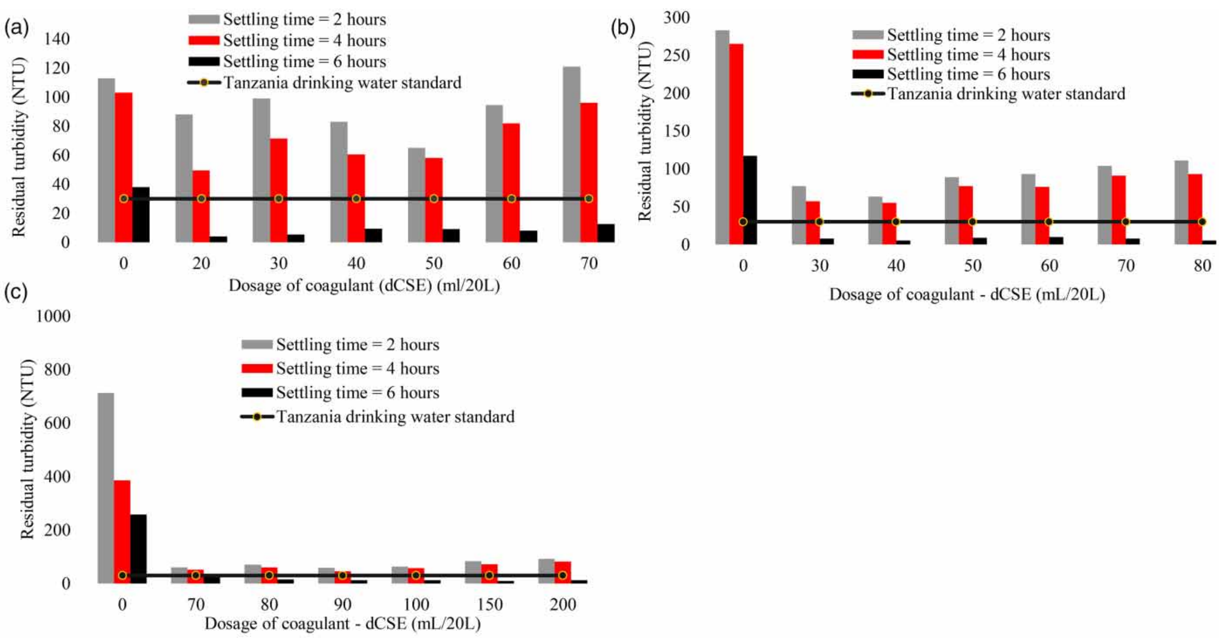

Figure 2 | The effect of varying dCSE dosage and settling time on coagulation of water with initial turbidity of (a) 150 NTU, (b) 450 NTU and (c) 1,000 NTU.

turbidity in treated water which had the initial turbidity of 150 NTU (Figure 2(a)), 450 NTU (Figure 2(b)) and 1,000 NTU (Figure 2(c)) were 4 NTU (97.3% removal efficiency), 8 NTU (98.2% removal efficiency) and 16 NTU (98.4% removal efficiency) at minimum dCSE dosages of 20, 30 and 80 mL/L, respectively. These minimum residual turbidities which were observed after 6 h of settling time of the treated water are within the Tanzania drinking water standard of 30 NTU (TZS 789:2008). In terms of turbidity removal efficiency, the results revealed that the performance of dCSE in water clarification increased with an increase in initial water turbidity which was accompanied by the corresponding increase in optimum dosages.

There was no further reduction in residual turbidity at dosages above the observed optimum ones, and at exceedingly high dosages, it was accompanied by increasing residual turbidity, a phenomenon referred to as restabilization of the destabilized floc particles. The occurrence of the restabilization process has also been reported by Bhuptawat *et al.* (2007) during coagulation of synthetic turbid water using undefatted crude seed extracts of *Moringa*.

Moreover, Figure 2(a)–2(c) shows that turbidity removal efficiency of untreated (control) reached 74% which revealed that plain sedimentation contributed significantly in clarification of turbid water, even though the residual turbidities were beyond the WHO (2008) and TDWQS guidelines, which specify the turbidity of safe drinking water to be less than 5 and 30 NTU, respectively.

According to statistical analysis (ANOVA) the value of P was less than 0.001 meaning that there is a significant difference between the control and treated water using dCSE, and thus *Moringa* seed had contributed significantly to the decrease in suspended solids.

It has been reported by other researchers dealing with natural coagulants based on plant seeds that the crude seed extracts are not efficient in coagulation of low turbid water due to limited inter-particle collisions in such waters in which the suspended particles are dispersed (Gregory & Duan 2001). However, Tanzanian rural women do not coagulate low turbid waters using *Moringa* seed powder, but rather they just filter the raw water through a piece of nylon cloth to remove particulate matter before use for drinking and other domestic purposes.

Figure 3 portrays that rural women seldom obtain sufficiently clarified water because they lack knowledge and technological guidance on how to use these natural and locally available coagulants correctly (Marobhe 2008).

Effect of dCSE coagulation on bacteria

The results presented in Figure 4 show the effect of dCSE on the removal of intestinal pathogens indicators in water

Figure 3 | Rural women in Tanzania using the incorrect technique to coagulate turbid water using *Moringa* seed powder (Marobhe 2008).

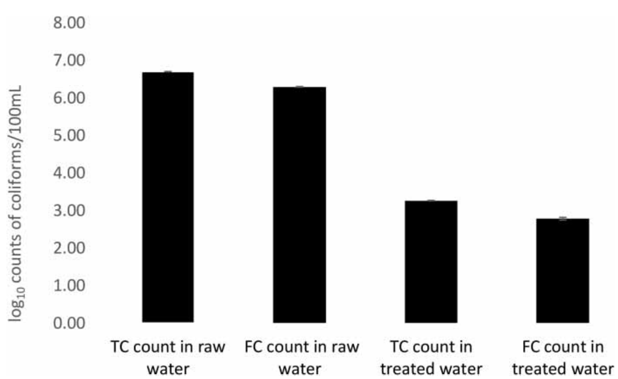

Figure 4 | The average density of TCs and FCs ($\log_{10}$ coliforms/100 mL) in water treated with dCSE after 6 h of settling time based on three analyses.

with an initial turbidity of 1,000 NTU after coagulation and 6 h of settling time. The density of TCs was reduced from $\log_{10}6.69$ to $\log_{10}3.3$ TC/100 mL with a removal efficiency of 51.3%. Similarly, FCs were reduced from $\log_{10}6.3$ to $\log_{10}2.8$ FCs/100 mL with a removal efficiency of 55.8%. Despite the remarkable removal of bacteria in coagulated water, the water did not comply with WHO guideline and Tanzania drinking water quality standard (TBS 2008) of zero (0) coliforms counts. It has been reported that the reduction of bacteria in the water treated by the CSE of *Moring* could be due to the antimicrobial activity of peptides which are present in most plant species (Broekaert *et al.* 1997). However, the fact that the coagulation–flocculation process during water treatment enhances turbidity removal and adsorption of other suspended matter cannot be disregarded. These results imply that additional treatment is needed for further destruction of intestinal pathogens to make water safer for consumption.

Effect of filtration on clarification of water treated by dCSE

It is common to see women in rural areas use pieces of cotton cloth materials to filter water to reduce suspended matter prior to drinking, which they call *kuchujamaji*. The same principle was applied in this study work but muslin material was used instead of cotton cloth to filter water pretreated with dCSE coagulant. The filtered water quality in terms of turbidity, pH and color is presented in Table 2. The results revealed that residual turbidity of water with an initial turbidity of 1,000 NTU treated by dCSE was reduced to 12 NTU and then to 4 NTU after filtering using the muslin material. The results show that water filtration was able to reduce residual turbidity in the pretreated water using dCSE from 12 to 4 NTU (66% removal efficiency). The filtration process may have most probably removed the dissolved materials which precipitated during the aeration process which occurred during the coagulation–flocculation process, and hence avoided obstruction of solar penetration through the water during SODIS. This precipitation possibility is in good agreement with what has been reported by previous researchers that the dissolved materials especially phosphates, iron and manganese ions are precipitated during the water coagulation process and hence settled along with other flocculated suspended matter (Abiyu *et al.* 2018).

Moreover, the results also showed that coagulation and filtration of raw river water samples which were initially light brown colored were transformed into clear water which was no longer objectionable for drinking. The average residual color of water after the coagulation–flocculation process and filtration were 41.3 and 26 MgPt-Co/L, respectively, which comply with the drinking water quality standard set by Tanzania. Despite the fact that the dCSE had high level of colored materials, it did not impart the color into the treated water possibly because the amount of dCSE used for water coagulation were very low ranging from about 1–4 g/20 L of water with different turbidity levels. Santos *et al.* (2012) affirmed that *Moringa* seed protein has the capacity to remove color and other humic acids which impart color into natural water sources. Moreover, the final pH of water treated

Table 2 | The effect of cloth filtration on final drinking water quality parameters

Quality after coagulation	Removal efficiency	Quality after filtration	Removal efficiency	WHO STD	TZS
Turbidity (Initial value = 1,000 NTU)					
12 (9–16) NTU	98.7% (98.4–99.1%)	4 (2–6) NTU	66% (50–83.3)	5 NTU	30 NTU
Color (Initial value = 398 MgCo-Pt/L)					
41.3 (38–45)	89.6% (88.7–90.4)	26 (19–33)	37% (36.7–53%)	5	50
pH					
6.86 (6.6–7.0)	N/A	6.9 (6.55–7.2)	N/A	6.5–8.5	6.5–8.5

Note: Shown in parenthesis are the ranges of residual turbidity.

using dCSE complied with both the WHO and Tanzania standards for drinking water. Unlike conventional chemical coagulant ($Al_2(SO_3)_4$) which significantly lowers the pH of coagulated water, the pH of water treated by *Moringa* dCSE showed negligible variation in pH most probably due to the natural buffering capacity of the seed extracts (Delelegn *et al.* 2018).

These results suggest that it is possible to improve the water quality through the filtration process using the proper low-cost materials at household level. However, the filter materials should be washed clean and disinfected to reduce microbiological contaminants. In order to ensure that the water is clean and safe for drinking, it is recommended that the water should be coagulated and solar disinfected before use.

Solar irradiance and temperature of water in PET bottles

Figure 5 shows solar irradiance measured on the elevated concrete surface where SODIS experiments and controls were also mounted. Wilson & Andrews (2011) revealed that among the key factors which facilitate SODIS efficacy is the total amount of solar light which encompasses the UV-A and visible irradiation available for the inactivation of pathogens. The results from this study showed that the average solar irradiance measured from 8.00 a.m. to 4.00 p.m. ranged from 430.8 to 1,146.3 W/m^2 with high values observed from 12 noon to 2 p.m. Along with solar irradiance records, high water temperature in PET bottles were observed between 12 noon and 3 p.m., the period when high solar irradiance which ranged between 995 and 1,146.3 W/m^2 prevailed. The water temperature in non-painted bottles and painted bottles irrespective of the water depths from 12 noon to 3 p.m. ranged between 38.7 and 43.9 °C and 40.8 to 44.2 °C, respectively. The paired t-test ($p = 0.05$) revealed that the water temperature in non-painted and painted bottles in half-filled and fully filled PET bottles did not vary significantly with *p*-values of 0.62–0.83, respectively.

The effect of solar irradiation on residual bacteria in the water pretreated with dCSE

Table 3 shows the disinfection effect of solar radiation on TCs and FCs after 3 h interval of solar exposure for a total period of 9 h of exposure period of unpainted and painted PET bottles filled with clarified water. The reduction of coliforms increased with an increase in exposure time of water to solar radiation. However, sunlight exposure time for 6 h mostly between 12 noon and 2.00 p.m. when maximum water temperatures of 44.2 °C and solar radiation of 1,146.3 W/m^2 at 2.00 p.m. prevailed, was established to be the effective exposure time for maximum in the activation of fecal pollution indicators. The removal efficiencies of TCs and FCs after 6 h of sunlight exposure water in painted and unpainted PET were 99

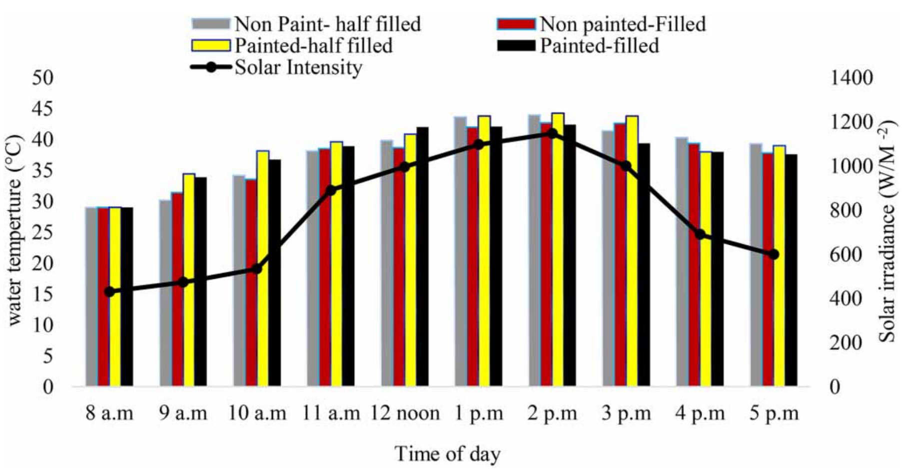

Figure 5 | Relationship between solar irradiance and water temperature in painted and non-painted bottles with different water volumes.

Table 3 | Removal of coliforms during different exposure time of water in unpainted PET bottles

Fecal indicators		**Fecal indicator density prior SODIS (log cell no/100 mL)**		**Average fecal indicators after SODIS (log cell no/100 mL)**	
Exposure time		0 h	3 h	6 h	9 h
Unpainted bottles	TCs	3.25	0.075 (**97.7%**)	0.032 (**99%**)	0.023 (**99.3%**)
	FCs	2.67	0.189 (**93%**)	0.065 (**97.6%**)	0.043 (**98.4%**)
Painted bottles	TCs	3.25	0.055 (**98.3%**)	0.003 (**99.9**)	0.032 (**99%**)
	FCs	2.699	0.108 (**96%**)	0.032 (**98.6%**)	0.016 (**99.4%**)

Bold values represent the percentage removal of coliform at different exposure time of water in unpainted PET bottles.

and 97.6%; 99.9 and 98.6%, respectively. Since the FC and TC are still higher than that acceptable according to Tanzania standard (TZS 789:2008) of 0 FC counts/100 mL, it is recommended to further boil water to kill all residue bacteria. It is expected that the energy to be used for boiling will be lower than those which will be used to disinfect untreated water.

Maximum water temperatures of 43 °C inside 1.5 L PET bottles during SODIS studies have also been reported by Castro-Alférez *et al.* (2017). Moreover, Wilson & Andrews (2011) observed that bacteria contaminants removal was achieved from 3 to 6 h for natural TCs and up to 2 h for natural FCs when applying solar radiation. These results are quite similar to those reported by Polo-López *et al.* (2019) who observed that 500 kJ/m^2 or 4 h of solar exposure of 1.5 L PET bottles under natural sunlight destroyed most pathogen indicators and waterborne pathogenic bacteria. Studies by Heaselgrave *et al.* (2006) showed that polio virus was also inactivated under simulated SODIS laboratory conditions at 850 W/m^2 and water temperature of 25 °C in under 6 h, while viral particles were all completely inactivated (3 log unit reduction) in less than 3 h of full sunshine. Also, McGuigan *et al.* (1998) reported that an increase in water temperature is a principal factor for the inactivation of bacteria in solar irradiated water although SODIS could be elicited by UV inactivation, thermal heating and synergy between both processes at temperatures above 45 °C. SODIS studies conducted by Berney *et al.* (2006) have shown that the inactivation of FCs by SODIS is triggered by distracting a sequence of normal cellular functions which culminates into loss of culturability.

Protocol for water purification in rural households and water safety

For convenience of a rural woman who carries out all household tasks including water collection, treatment and storage, the coagulation–flocculation process could start between 9 and 10 p.m. just before people go to bed. This process will take 2–3 min to disperse the dCSE in the turbid water, and thereafter the water is left for flocculation for 25–30 min. Thereafter, the flocculated water should settle undisturbed from about 10.30 p.m. to 5.00 a.m. (6–7 h) followed by water filtration through special muslin material. The water is then filled in clean 1.5 L PET bottled and subjected to SODIS treatment between 10.00 a.m. and 4.00 p.m. with maximum exposure time of 6 h. For optimal SODIS performance, all PET bottles should be placed on corrugated metal sheets to allow maximum water temperature build up. However, exploring a large volume of 20 L transparent plastic containers which are already in use in Tanzanian communities, will expand the use of SODIS as they are affordable and also reduce the tedious work of filling a large number of 1.5 L PET SODIS bottles sufficient for the household needs for safe drinking water. The use of 20 L transparent polypropylene (PP) buckets has also been reported by Polo-López *et al.* (2019) to be effective in the inactivation of bacterial, viral and protozoan.

The safety and shelf life of the treated water should not be doubted because most rural households store drinking water in clay pots (capacity 10–30 L). The overnight stored water in the clay pots have the temperature of around 10 ± 3 °C which improves water palatability and also inhibits regrowth of bacteria due the low water temperatures (Marobhe 2008).

CONCLUSIONS

The dCSE of MO, a locally available natural coagulant, effected substantial improvement in physical and bacteriological quality of turbid water and rendered water filtration and inactivation of fecal pathogens by solar irradiation feasible. More specifically,

- The dCSE at optimum dosages of 20, 30 and 80 mL/20 L with an initial turbidity of 150, 450 and 1,000 NTU coagulated water and produced water with a residual turbidity of 4 NTU (97.3% removal efficiency), 8 NTU (98.2% removal efficiency) and 16 NTU (98.4% removal efficiency), respectively, after 6 h of settling time. These residual turbidities are within the Tanzanian drinking quality water standard of 30 NTU.
- Filtration of turbid water (1,000 NTU) clarified with dCSE reduced suspended solids from 12 to 4 NTU which is 66% removal efficiency. The final water pH and color after the treatment process complied with the Tanzania drinking water quality standards.
- The dCSE flocculated suspended particles along with bacteria in which TCs and FCs were reduced by 99.9 and 99.6%, respectively, after 6 h of settling time of treated water.
- Solar irradiation of water pre-clarified by the dCSE filled in unpainted and painted PET bottles for a minimum effective period of 6 h reduced TCs and FCs by 99 and 97.6%, and 99.9 and 98.6%, respectively.
- It is recommended that a rural woman should start the coagulation–flocculation process of turbid water using dCSE between 9 and 10 p.m. just before going to bed and water settling should end around 5 a.m. Thereafter, expose the filtered water to natural sunlight between 10 a.m. and 4 p.m. It is proposed that solar disinfected water should be stored in clean traditional clay pots.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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