IMPROVEMENT OF WATER QUALITY USING A TRIANGULAR SOLAR STILL

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ABSTRACT

Water-related disasters can pollute existing clean water supplies with unwanted substances, which result in water scarcity. Even though there are technologies that can provide water-relief during disaster periods, these solutions can be expensive, require electricity, or may be unable to treat seawater (salt water). Hence, we have developed a Triangular Solar Still (TrSS) to produce distilled water. To ensure that the resulting distilled water was potable, we measured seawater ion content, iron content, nitrate content, total organic carbon, odor, and total and fecal coliforms, which are important parameters during disaster periods. In the experiment using seawater, seawater was distilled, and the output water had a mineral composition of 0.001 mg/L Cl^-, 1.3 mg/L Na^+, 0.1 mg/L Mg^{2+}, 0.4 mg/L SO_4^{2-}, 1.4 mg/L Ca^{2+}, and 0.7 mg/L K^+, which is similar to the ion concentrations found in distilled water. After distillation, iron was not detectable, while nitrate was reduced to 3.7 mg/L. The variables measured in the distilled water produced from seawater and water high in iron and nitrate were lower than water quality guidelines determined by the WHO or the Japan Ministry of Health, Labour and Welfare. Water needed to be distilled at least three times to reduce the total organic carbon level below the Japanese guideline of 3.0 mg/L for drinking water and to eliminate the vinyl odor from the cover film. In addition, the TrSS sterilized total and fecal coliforms with solar ultraviolet radiation. The results show that a TrSS can produce potable, distilled water during water-related disasters.

Keywords: Water-related disasters, triangular solar still, distillation, distilled water, water quality

1. INTRODUCTION

When a disaster happens, water resources are often negatively impacted. Water-related disasters such as floods and storms account for approximately 90% of the natural disasters that occurred between 1998 and 2017 and affected approximately 4.3 billion people around the world (Wallemacq and House, 2018). Even after a disaster ends, its effects remain, which include a lack of clean water resources. Municipal water can be contaminated by seawater or wastewater associated with the disaster. In addition, while well water may be less vulnerable to surface contamination, it may be contaminated with underground iron. Consuming unsanitary water can cause health problems such as hypertension (Scheelbeek et al., 2016), diarrhea (Mehtab et al, 2017), and hemochromatosis (Marianne, 2017).

Various water treatment technologies have been deployed to provide water relief during post-disaster periods, which include desalination (Lei et al., 2018) and coagulation and flocculation (Tzoupanos and Zouboulis, 2008). Seawater can be desalinated to freshwater using a desalination plant. However, the high cost of desalination makes this process unsuitable for less-developed countries, and its electrical energy requirement may make the process unavailable during post-disaster periods. Coagulation and flocculation products are popular during emergencies because they are cheap and remove dirt, heavy metals, and bacteria; but these processes are unable to desalinate seawater. Although various measures have been taken by governmental and non-governmental organizations to reduce water scarcity during post-disaster periods, water quality remains a serious problem. According to a survey conducted in Aceh by CARE and the Provincial Health Office after the 2004 Indian Ocean Tsunami, 1 out of 11 water tankers tested positive for E. coli. In addition, despite the active promotion of boiling water before drinking, 47.5% of the 400 water samples taken from water stored in homes tested positive for E. coli (Clasen et al., 2006). These examples highlight why securing safe drinking water is important, especially during and after disasters.

For these reasons, we have developed a low-cost solar still, the Triangular Solar Still (TrSS), to produce distilled water (Kato et al., 2019). The TrSS has a relatively simple structure that consists of a cover film passed through a triangular bamboo frame and a trough that holds raw water (See Figure 1). The TrSS is also lightweight, which allows most people to carry it easily. Distilled water is obtained by evaporating and then condensing the raw water using only sunlight as the source of energy.

The TrSS fabrication process can be described as follows (Figure 2).
(1) Draw and cut polyolefin films (inner and outer film) following the assembly diagram.
(2) Heat weld overlaps between the cut sections to construct covers.
(3) Cut bamboo sticks and tie them together to form a triangle.
(4) Cut plywood following the templates.
(5) Paint the plywood black and assemble the trough.
(6) Cover the trough with the inner film.
(7) Assemble the frame.
(8) Install the trough and place it on the triangle frame base.

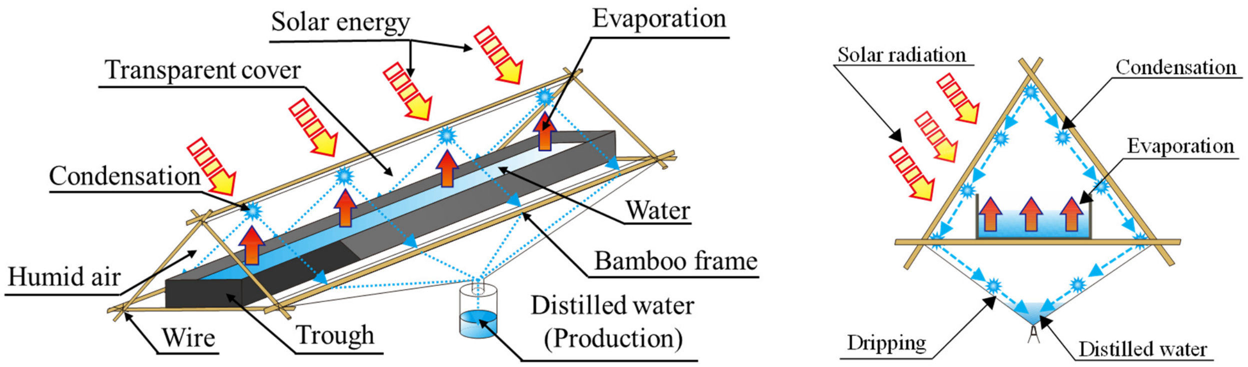


Figure 1 Composition of Triangular Solar Still and process of water purification.

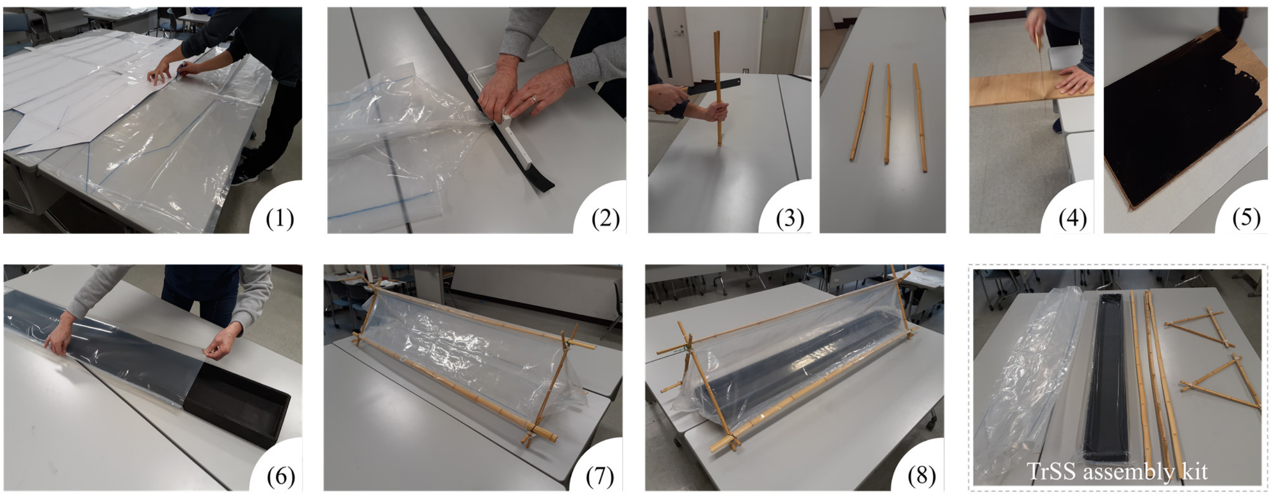


Figure 2 Fabrication process of a TrSS.

Past studies have focused on enhancing water production (Chiavazzo et al., 2018, Feilizadeh et al., 2016, and Vivek and Ajeet, 2016), but fewer studies have been conducted on the quality of distilled water from the TrSS. This paper presents the results of water quality improvement using the TrSS for distillation. The variables investigated were seawater content, iron content, nitrate content, total organic carbon, and total and fecal coliforms.

2. EXPERIMENTAL OUTLINE

Experiments were divided into indoor experiments (seawater content, iron content, nitrate content, and total organic carbon [TOC]) and outdoor experiments (total and fecal coliforms). Table 1 shows the type of raw water, content variables, and the measuring instruments used for each experiment.

Table 1. Raw water, content variables, and measuring instruments of each experiment.

Experiment	Raw water	Content variables	Measuring instruments
Seawater content	Seawater, taken from Mikuni Sunset Beach in Fukui Prefecture	a) pH b) Electrical conductivity (EC) c) Sodium ion, Na^+ d) Potassium ion, K^+ e) Calcium ion, Ca^{2+} f) Chloride ion, Cl^- g) Magnesium ion, Mg^{2+} h) Sulfate ion, SO_4^{2-}	a)-e) LAQUA twin compact meters (HORIBA) f) SALMATE-100 (Chuken Consultant Co. Ltd.) g) DR1900 Portable Spectrophotometer (HACH) h) Hanna checker, Magnesium hardness handheld colorimeter (HANNA Instruments)
Iron content	Iron water, made by placing rusted nails in water	Iron, Fe	Hanna Checkers, Iron Handheld Colorimeter (HANNA Instruments)
Nitrate content	Secondary-treated wastewater, taken from Goryougawa Treatment Center	Nitrate, NO_3^-	LAQUAtwin compact meter (HORIBA)
Total Organic Carbon and Odor	Tap water	a) Total Organic Carbon, TOC b) Odor level	a) DR900 Multiparameter Portable Colorimeter (HACH) b) Odor level meter (New Cosmos Electric Co. Ltd.)
Total and Fecal Coliforms	Secondary-treated wastewater (Coliform number of ~10000/mL), taken from Goryougawa Treatment Center	a) Total coliforms b) Fecal coliforms	Coliform Detection Paper (Suncoli, SUN CHEMICAL Co. Ltd.)

Distillation of water in the indoor experiments was performed in a thermostatic chamber with room temperature set to 20°C. The TrSS was placed under lamps that had a total intensity of 1200 W, which were adjusted using a variable transformer and verified by a pyranometer, and fanned for a duration of 8 hours (See Figure 3). In the seawater content, iron content, and nitrate content experiments, the variables were measured for both raw water (before distillation) and the corresponding distilled water to verify the removal of these compounds by distillation. In contrast, experiments to measure TOC and odor were done simultaneously and both variables were tested in only the distilled water. Because organic carbon on the cover film can affect the quality of the resulting distilled water, the number of distillations needed to reduce the organic carbon level below the Japanese guideline was also examined. The TOC levels were measured because organic compounds can leach from the cover film into the condensed, distilled water. In addition, odor was measured in order to examine the effect of the vinyl cover film on the distilled water.

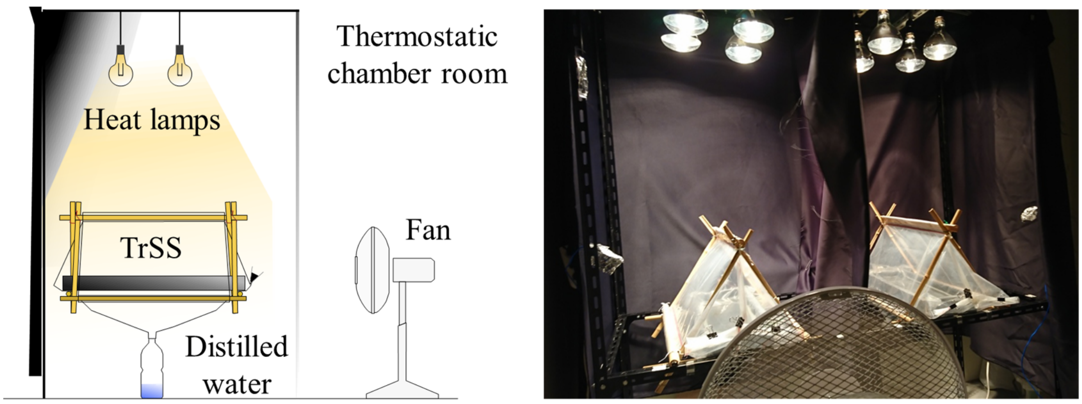


Figure 3 Indoor experiment.

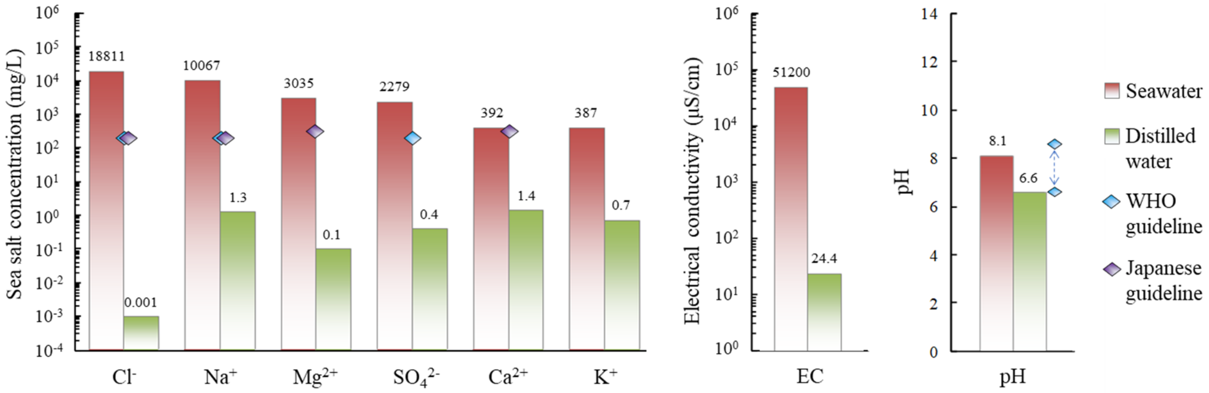
At the same time, outdoor experiments were carried out on sunny days between 12:00 a.m. to 9:00 p.m. during August and September 2018 on the rooftop of the University of Fukui. Ultraviolet (UV) light intensity inside the TrSS, R_{uv} (W/m^2), was measured using a UV meter (T&D Corporation), while the temperature of the trough water, T_w (°C), inside air temperature of TrSS, T_{in} (°C), and outside air temperature, T_{out} (°C), were measured using thermocouples. Both trough water (between 12:00 a.m. to 9:00 p.m.) and distilled water (between 1:00 p.m. and 9:00 p.m.) were measured seven times for total and fecal coliforms.

3. RESULTS AND DISCUSSIONS

3.1 Indoor experiments

As shown in Figure 4, the concentrations of ions, with the exception of magnesium, pH, and EC, in the seawater used in this experiment were similar to those in typical seawater (Millero et al., 2008 and Tyler et al., 2017). In our experiment, the concentration of Mg^{2+} ions in the seawater was higher than that found more typically in seawater (1300 mg/L). This was likely due to the narrow measurement range of our instrument (up to 2.0 mg/L), which required the seawater to be highly diluted and may have caused inaccuracies. This, however, does not apply to the measurement of Mg^{2+} ions in distilled water.

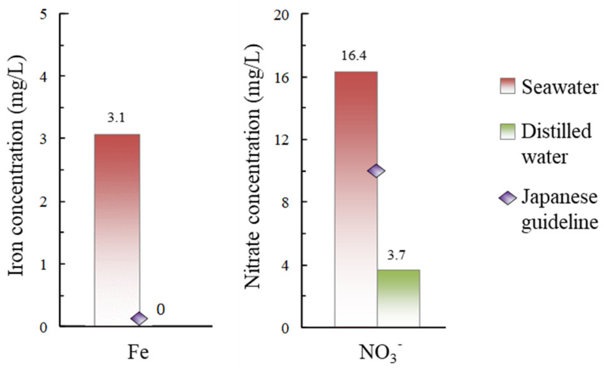
Sea salt ions in distilled water were almost completely removed by distillation and had concentrations of 0.001 mg/L Cl^-, 1.3 mg/L Na^+, 0.1 mg/L Mg^{2+}, 0.4 mg/L SO_4^{2-}, 1.4 mg/L Ca^{2+}, and 0.7 mg/L K^+. The pH went from slightly alkaline to near-neutral with distillation. The concentration of sea salt ions and the pH of the distilled water were under the water quality guidelines of WHO (WHO, 2017) and Japan (MHLW, 2003). EC of the water distilled by the TrSS was near the normal range for distilled water (1-10 μS/cm) and below that of freshwater (300-800 μS/cm) (Rusydi, 2018); thus, the distilled water was safe for human consumption. These results showed that potable drinking water may be produced from seawater (or saline water), which is especially helpful to those affected by disasters in or near coastal areas.



a) Concentration of sea salt ions b) Electrical conductivity c) pH

Figure 4 Seawater content.

As shown in Figure 5, the initial iron concentration in raw water was 10 times higher than that of the Japanese water quality guideline (0.3 mg/L), but with distillation, iron concentration was below the detection limit. In addition, the initial nitrate concentration in raw water was 1.5 times higher than that specified in the Japanese guidelines (10 mg/L). After distillation, nitrate in the distilled water was reduced to about a quarter of its initial value and was below that of the Japanese guidelines. These results showed that iron and nitrate can be reduced in contaminated water (i.e. wastewater or well water) using the TrSS.



a) Iron b) Nitrate

Figure 5 Iron and nitrate content.

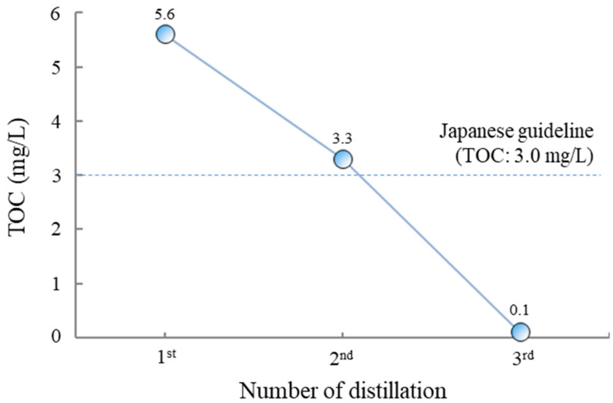


Figure 6 Total organic carbon of distilled water.

In the TOC experiment, the initial TOC concentration was 5.6 mg/L. After the third distillation using the TrSS, this value dropped to 0.1 mg/L, which is below the Japanese water guidelines of 3.0 mg/L, (Figure 6). At least three times of distillations are needed before the water can be used for drinking purposes because water from the first few distillations can contain an unsafe level of organic carbon from the cover film. After each distillation, the odor level of the distilled water decreased rapidly and was reduced to approximately half of the initial odor level after 24 hours. The vinyl odor of freshly distilled water can be detected by smell but completely disappears after just a few hours.

3.2 Outdoor experiment

Figure 7 shows results that were typically found for the number of total and fecal coliforms. Both total and fecal coliforms in trough water were detected between 12:00 a.m. and 10:00 a.m. but became undetectable after 1:00 p.m. The removal of these coliforms was thought to be associated with either water temperature or UV exposure.

Figure 8 and Figure 9 show the variation of the T_w, T_{in}, T_{out}, R_{uv}, and ΣR_{uv} with time. The value of T_w reached 50.5°C at 1:30 p.m., but this temperature was not high enough to remove the fecal coliform, which have a sterilization temperature of 65°C (Spinks et al., 2006). Hence, we assume UV exposure is responsible for fecal coliform removal. R_{uv} and ΣR_{uv} were 21.9 W/m^2 (at 10:30 a.m.) and 484 kJ/m^2, respectively. The same level of sterilization can be expected during periods of disaster especially if conditions are sunny and hot.

In addition, total and fecal coliforms were not detected between 1:00 p.m. and 9:00 p.m. Additional tests were conducted on three other days, and total and fecal coliforms were not detected in distilled water. Thus, these results showed that the solar water disinfection of the TrSS is useful in purifying drinking water.

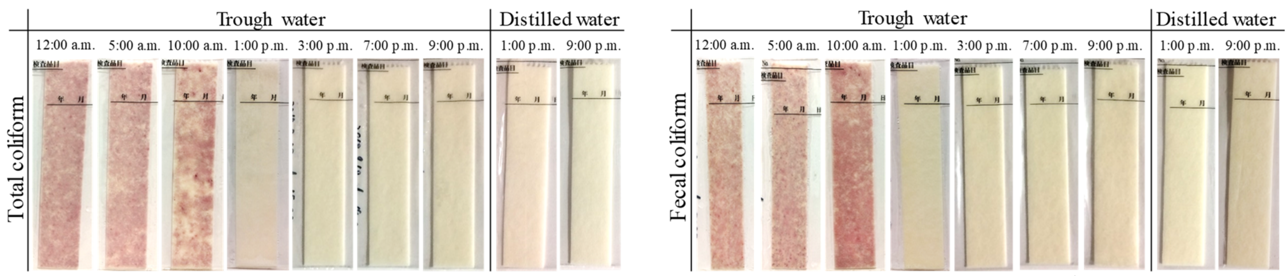


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Figure 7 Total and fecal coliforms in trough water and distilled water.

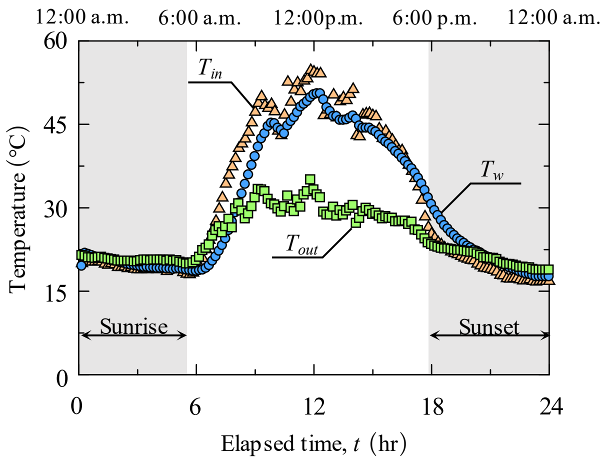

Figure 8 Time variation of each temperature.

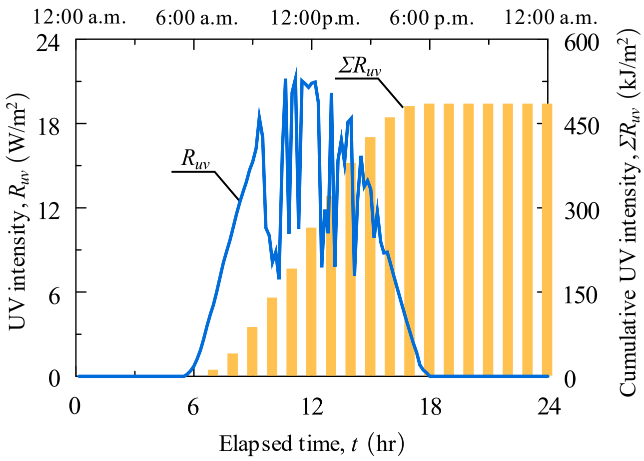

Figure 9 Variation of UV intensity with time.

4. CONCLUSION

The objectives of this study were to analyze the improvement of water quality using the TrSS and to identify its potential use during disaster periods. This study showed that the TrSS was able to remove salt ions from seawater and produce distilled water. The TrSS can also reduce iron and nitrate concentrations in contaminated water. It is advisable for distillation to take place at least three times before using the water for drinking. In addition, the results showed that waiting at least a few hours after distillation helps remove the vinyl odor of the cover film from the distilled water. In addition, the TrSS is able to reduce total and fecal coliforms and has a sterilizing effect. Therefore, the TrSS can produce potable, distilled water for drinking purposes during periods of disaster. Further research will examine additional water quality parameters and the development of the TrSS as a water relief kit.

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