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A Solar Disinfection Water Treatment System for Remote Communities

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Abstract

Worldwide, approximately 780 million people do not have access to safe and clean water for drinking, cooking or washing. Consumption of untreated water exposes humans to a range of contaminants including faecal-borne pathogens and chemical pollutants. As a consequence, it is estimated that 1.5 million people die each year as a result of the consumption of untreated or contaminated water. These deaths are preventable with access to clean and safe water, but capital costs and maintenance requirements for large-scale treatment systems are prohibitive and challenging to implement in remote or distributed communities. Such remote communities typically suffer from faecal contamination of transient water sources, rather than chemical or radiological contaminants. To address this problem a low-cost continuous-feed water treatment facility has been designed and developed. The facility utilises solar (UVA) radiation to treat pathogens. Additionally, the facility is designed such that it can be manufactured in-situ from limited or improvised resources at low capital and maintenance costs. The system is modular so that multiple systems can be used to increase water treatment capacity as required. Testing indicates that 3 modules of

the design can treat 34L of water in 4 hours producing a 4-log reduction in E. Coli (from 8×10^5 CFU/ml) with a residence time of less than 30 minutes. This is based on an average solar-based UVA flux ranging from 24 to 36 W/m^2 (time average of 28 W/m^2).

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1. Introduction

1.1. Clean water: A humanitarian crisis

The importance of access to safe drinking water was reflected in target 7B of the UN Millennium Development Goals (MDGs), which sought to halve the percentage of population (from 1990 to 2015) without sustainable access to an improved drinking water source [1]. According to JMP [2], this goal has been achieved. Furthermore, such efforts to improve access have been credited with reducing drinking water related deaths by 31% [3]. Nevertheless safe drinking water is not currently accessible to over 780 million people [4]. Drinking contaminated water has been estimated to contribute to 1.5 million deaths annually, with over 90% of cases being children [4]. Existing water sources are increasingly at risk of contamination, and population growth is driving a greater demand for clean water. Subsequently, there is still a need to improve the quality and quantity of potable water to developing nations, and make these systems affordable and useable to the end user. This is a particular challenge in remote and developing areas where it is often unviable to implement large-scale water decontamination and storage.

1.2. Papua New Guinean communities

Papua New Guinea is one of the most underdeveloped countries in the world. It has a population of approximately 6.9 million people, with 87% living in the rural mountainous regions, making infrastructure transportation a difficult challenge [2]. Although the country is resource-rich, with oil, gas and minerals contributing to the national economy, 37% of the population is in poverty [5] and political instability has resulted in a decrease in living standards since the 1990s [6]. According to the Department of National Planning and Monitoring 2010, only 40% of the population has access to safe water [7]. Statistics from the World Health Organization [3], show that 4,900 people die per year from Water, Sanitation & Hygiene (WASH) related illnesses, which is approximately 10% of the total deaths in PNG. Considering these deaths are preventable, it is evident that appropriate solutions for PNG need to be developed and implemented.

Many villages in PNG use large communal rainwater tanks to collect water in the wet season, which is supplemented with river water in the dry season. Although rainwater is generally pathogen-free and has the lowest capital and ongoing costs out of all the improved water sources [8], the collection and storage of rainwater is not necessarily pathogen-free. Excretion and corpse decomposition of insects, birds, rodents and small mammals on, or above, the catchment area can introduce pathogens into the collected water and storage container [9]. Additionally, fecal pathogens can survive for an extended period during storage within rainwater tanks [10]. Subsequently, a system that can treat communal rainwater without the need for long-term storage of the treated water, is necessary to improve water quality and minimize recontamination.

The average maximum temperature for the capital city of PNG, Port Moresby, is approximately $26^{o}C$. The average monthly rainfall ranges from 25 mm to 198 mm, with a total yearly average of 1084 mm [11]. The cloud cover throughout the year is fairly constant with 19% of time overcast, 39% mostly cloudy, 31% partly cloudy and 14% mostly clear. There is an additional 19% of the time with missing data [12]. From a preliminary assessment, there is both sufficient sunshine and rainfall to warrant a solar-based rainwater treatment system in PNG.

1.3. Health concerns from water contamination

In terms of waterborne contaminations, bacteria including Salmonella, Shigella, Escherichia coli and Campylobacter are the major contributors [13]. The ingestion of water contaminated by such bacteria can result in illnesses such as cholera, gastroenteritis and typhoid fever. These illnesses can cause excessive vomiting, severe fever, uncontrollable losses of bodily fluids and eventually death due to extreme dehydration and body organ shutdown. The pathogens that cause these waterborne diseases are the primary concern in humanitarian interventions as they are widespread but easily preventable [14]. Therefore, the current work is focused on the treatment of pathogens in water, rather than physical, chemical or radiological contaminates.

1.4. Potential water treatment mechanisms

There are numerous water treatment systems available to deactivate pathogens. Developed countries can typically afford to use complex systems dependent on chemical and filter treatment. These systems ensure supplied water meets national and international standards. However, the infrastructure, operation, maintenance and supply costs are prohibitive in many developing nations. The focus of the current work is on designing a system that does not rely on chemical, mechanical or electrical inputs, but rather passively utilizes energy collected from the sun. There are a number of existing water treatment systems that may utilize available solar energy: pasteurization, distillation, photocatalysis and disinfection. Each method has advantages and disadvantages that need to be considered when designing water treatment systems for a particular application. This current work is focused on small-scale applications in undeveloped small communities (remote and mountainous PNG villages), where there is a lack of technical and material resources.

Irrespective of treatment mechanisms, the system design must also consider factors such as implementation and operation. Local integration is fundamental in developing a long-term water solution [15-17]. Water supply and treatment investments totaling US$215-360 million have failed in Africa due to the inability of local communities to accept accountability for the infrastructure or technologies implemented on their behalf [16]. It is therefore necessary to develop a system with, and not just for, end-users. This can be achieved by simply providing design guidelines and having the local communities build and install systems. Such a system needs to be able to be constructed from locally available materials (as far as possible), function simply without user intervention, and be robust enough to survive the conditions. However, the operation of a solar thermal system is subject to diurnal and seasonal solar cycles; meteorological events (such as rain and cloud cover); and global and local locations. Any system should be designed to accommodate these variations of solar radiation without compromising the safety of the produced water.

1.4.1. Solar pasteurization

Pasteurization involves heating water to a sufficient temperature for a time in order to destroy pathogenic microbes [18]. The time taken to destroy microbes decreases exponentially with increasing temperature. A common misconception is that water must be boiled, as pasteurization occurs at temperatures well below 100°C. For example, worms and protozoa cysts are destroyed at temperatures above 55°C, whereas E. coli, Salmonella typhi, Vibrio cholera, Shigella spp and Rotavirus are destroyed at temperatures above 60°C. Therefore, a system that maintains water temperatures above 60°C may be suitable to address the pathogens that are of primary concern.

There are several examples of systems using the principle of solar pasteurization in the literature. Safapour and Metcalf [19] assessed a small solar pasteurization system that used aluminum foil reflectors and PET plastic bottles finding a 4-log reduction in E. coli within one hour. Although this system can potentially have zero capital and operational costs, it is limited to being a batch process capable of treating the volume of the bottle (that is typically less than 2 L).

Onyango *et al.* [20] investigated the performance of a flat plate collector capable of a quasi-continuous feed of water. The system used an automotive thermostatic valve that released batches of water once the temperature exceeded $83-84^{\circ}$C. The volume of water treated to a zero-count E. coli. was measured with and without reflectors to concentrate solar thermal energy. It was found that the system was capable of treating 95 litres and 49 litres per day with and without reflectors respectively [20]. Although the system was made from locally sourced materials, there is a non-trivial degree of complexity, which may be problematic in some environments.

Konersmann and Frank [17] presented an investigation into solar pasteurization using evacuated tubes with a thermostatic valve is used to release batches of water once the temperature is above 82°C. It was shown that a system with 48 evacuated tubes can produce in excess of 500 liters per day of treated water [17]. However, the cost of such a system is approximately US$500 and therefore significantly prohibitive.

1.4.2. Solar distillation

Distillation is the process of evaporating water and collecting the distillate. Distillation can successfully treat for microbiological contaminates, as well as physical, chemical and radiological contaminants. However, distilled and thus demineralized water has been shown to be harmful to the human body when consumed [21]. Additionally, distillation typically has low efficiency [22], but commonly used for seawater / saline water treatment. Solar distillation has been extensively studied [23-25]. The current project is focused on inland PNG with high rainfall and freshwater rivers. Consequently, low efficiency systems suitable for seawater will not be suitable.

1.4.3. Photocatalysis

Photocatalysis is a form of advanced oxidation process involving the production of hydroxyl radials (OH⁻) that attack oxidizable contaminants. Photocatalysis has been shown to oxidize almost any organic contaminant, typically used for treatment of organic pollutants, and is highly effective in the disinfection of microbial contaminants [26]. The hydroxyl radicals are formed through a light-induced reaction requiring O_2, water and a semiconductor catalyst. The semiconductor Titanium dioxide (TiO_2) is demonstrated to be the most active catalyst [26]. Additionally, TiO_2 is resistant to chemical breakdown, low cost, safe and readily available (in the developed world). Using TiO_2 the oxidation reaction can be induced by solar UV spectrum (up to 390nm). Photocatalysis has been shown as a successful system by numerous authors [27-30].

Although photocatalysis has been shown to deactivate organic compounds, the process is dependent on a number of factors including UV radiation, mass of catalysis, pH, temperature and oxygen concentration of the water. Additionally the TiO_2 must be held in suspension during treatment and recovered after treatment. For the current system, the requirement of a low maintenance and low complexity system invalidates the use of photocatalyic methods.

1.4.4. Solar disinfection (SoDis)

Solar disinfection (SoDis) is a water treatment technique consisting of exposing water to sunlight, specifically UVA radiation. Unlike conventional UV water treatment, where UVC radiation directly damages the DNA of pathogen, SoDis utilizes UVA wavelengths in order to form reactive-oxygen species (ROS) in water. These ROS, (which include monatomic oxygen, superoxide, hydrogen peroxide and hydroxyl radicals) damage the DNA of pathogens and deactivate the microbes [15].

Cells have a number of DNA repair mechanisms [15]. Ubomba-Jaswa *et al.* [31] showed that following SoDis treatment, microbe growth in contaminated water samples placed in the dark will continue if complete inactivation of pathogens has not occurred. However, continued inactivation post treatment occurs if a sufficiently high UVA dosage is applied [32]. It is proposed that the DNA repair mechanisms are overwhelmed and rendered inert. It is therefore necessary that SoDis treatment is undertaken immediately prior to consumption *or* the UVA dosage is sufficient to completely deactivate any pathogens.

Thermally enhanced SoDis occurs when water is exposed to UVA radiation and maintained at a temperature above $45^oC – 50^oC$ [15,33]. The higher water temperatures improve the efficiency of the pathogen deactivation, with an exponential relationship of efficiency to temperature. Thermal enhancement of SoDis improved efficiency by a factor of 1.7 at 45^oC, and an efficiency factor of 3 at 50^oC [15].

2. Equipment and testing procedure

Two types of tests have been conducted for the work presented in this study: laboratory-based water temperature testing and field-environment E. coli deactivation testing. These tests assess the new design effectiveness and the potential application of pasteurization, SoDis or thermally enhanced SoDis mechanisms to destroy water-borne pathogens in practice.

2.1. Measurement of temperature history

The water temperature testing was conducted using a linear array of seven 500-Watt halogen lamps (white-light). Although these lamps do not produce the same broadband radiation as sunlight, they were assessed to have comparable infrared radiation wavelengths, and thus suitable for assessing radiation-based heating. A pyrometer was used to provide a uniform distribution of radiation intensity, with the configuration providing an average intensity of between $480 - 500$ W/m^2 at the testing location. Temperatures were measured using a Texas Instruments LM335 two-terminal zenor system with accuracy and non-linearity of +/- 1K. An Arduino Uno ADC was used to enable data recording to a PC. The aim was to determine what temperature history and residence time each water sample would be exposed to under typical operating conditions.

2.2. E. coli deactivation testing

The correlation between coliforms and pathogens has been rejected or questioned by numerous studies [34-37]. Nonetheless, E. coli is commonly used as an indicator for pathogens caused by fecal contamination [38] and should not be present in potable water [21]. Additionally, the stance of the WHO is that indicator testing is a suitable means for assessing water quality, particularly in developing countries with limited resources [39]. Therefore, E. coli was tested for the current work.

The particular strain of E. coli was the Food Drug Administration "Seattle Strain" Escherichia coli American Type Culture Collection 25922. The Food Research Group at the University of Adelaide provided the sample.

Luria Broth Lennox (LB) 1.5%w/v was used as a liquid growth medium for all cultures. The E. coli strain was cultured before each test from a suspended refrigerated stock culture. Aseptic technique [40] was used to inoculate a single colony of the culture into a 30 mL test tube of LB, and the tube was incubated for eight hours at 37°C. Following incubation, 1 mL of the inoculum was pipetted into a 50 mL flask of LB and sealed with sterile cotton bung. This larger volume was then incubated for 16 hours overnight in a rotator shaker incubator to induce an aerobic growth environment. This ensured maximum growth of harvested cells with a uniform resistance to UV radiation. Bacterial cells were harvested from the growth media through centrifugation to minimize stress to the bacteria and increase chance of survival. Counts were consistently in the order of 10^{10} per mL.

Water samples of 2 mL were taken at regular intervals throughout the test from a specially installed septum in the centre of the reactor tube. Standard plating technique [40] was applied for each 2mL sample, with a 6-log dilution series.

The E. coli deactivation tests were conducted outdoors and using non-potable river water. This was to provide a realistic environment for assessment of solar-based UVA radiation. For these tests, UVA radiation was measured using an sgLux UV-Cosince-D UV sensor. The water was sourced from the River Torrens in Adelaide. Water turbidity was measured using the method of Myre and Shaw [41]. Visibility varied between 240 mm and 260 mm, equating to approximately 30 NTU (Nephelometric Turbidity Units). Water absorbance was measured using a 1 mm path-length quartz cuvette using a BioRad SmartSpec^{TM} 3000 Spectrophotometer, calibrated with reverse osmosis water. The water used had an absorbance ranging between 0.16 cm^{-1} and 0.05 cm^{-1} for frequencies ranging from 315 nm and 400 nm.

3. Results and discussion

3.1. Design considerations

Compound Parabolic Collector (CPC) profiles were selected to increase total UVA radiation to the contaminated water. One of the main advantages of a CPC system is that it is a highly robust concentrating collector in terms of alignment errors and collector profile inconsistencies [42]. Additionally, due to the geometry, CPC systems do not necessarily need to track solar paths, and therefore have minimal complications with installation, operation and maintenance. A schematic diagram of a CPC is shown in Fig. 1 and demonstrates the insensitivity to alignment of

the reflector with respect to the incoming solar radiation. Parabolic reflectors on the other hand are more efficient when perfectly aligned but require a mechanism to track the sun as it moves.
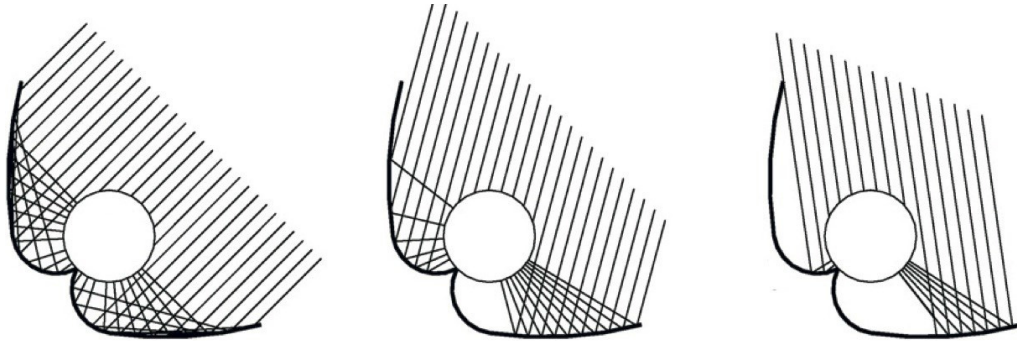

Fig. 1. Schematic diagram of CPC collectors with ray tracing representing path profiles of solar radiation [43].

The profile of the CPC designed has a collection factor of 1.3 and length of 900 mm. This provides an aperture area of $0.141 m^2$ and collection angle of 50.3^o. The reactor tube has an outer diameter of 50 mm. Detailed specifications and engineering drawings for the CPC, collector and system are provided online [43].

Two system types were developed: a workshop-quality manufactured system of high precision and high-quality materials; and a hand-made rudimentary system. The manufactured system has a 16 mm-thick plywood frame consisting of five ribs and four parallel beams. The ribs supported aluminum former plates that give the shape of the CPC. The CPC itself was made from aluminum sheet rolled and pressed into the former plates. The surface of the CPC was then coated with Mylar to give a high surface reflectivity. The reactor tube for the manufactured system is a Pyrex glass tube of 50 mm OD.

Three modules of the rudimentary system were made. Each module is 1.4 m long and has an 18 mm-thick plywood frame consisting of four ribs and three parallel beams. The ribs also acted as former plates to shape the CPC. The CPC itself was made from 1.5 mm HDPE sheet, cut, pressed and nailed to the frame. The surface of the CPC was then coated with metalized plastic (crisp packet wrappers). The reactor tube is 50 mm OD borosilicate glass, attached with two simple zincalume downpipe clips.

3.2. Potential of thermally-enhanced SoDis

In order to assess the possibility of thermally enhanced SoDis, temperature variations in the test facility were assessed. The manufactured system was placed under the array of lights. The Pyrex reactor tube was filled with approximately 1.25 liters of water at approximately $20^o C$. Temperature sensors were located at each end of the reactor tube. The system was orientated horizontally so as to avoid buoyancy-driven mixing within the tube.

Figure 2 shows the water temperature results. The results indicate that a batch of water would need to be exposed to solar radiation for over 40 minutes before the water reached the critical temperature required for the enhanced thermal SoDis effect. As the aim of the current work is to develop a continuous feed system, it is evident that enhanced thermal SoDis cannot be assumed to work.

3.3. E. coli deactivation

Two tests to assess E. coli deactivation under natural sunlight and using the manufactured system were conducted on separate days. In both cases, fixed volume of 1.25 L was used (i.e. zero mass flow rate) and the system was orientated at 33°, which is an optimal angle for solar radiation collection in Adelaide.

The first test, conducted on the 18th of September, 2013, had an initial E. coli concentration of 2.3×10^5 CFU/mL. The average UVA irradiance was recorded as 28 W/m^2. Samples were taken at least every 5 minutes. The concentration of E. coli was reduced to below detectable limits after 20 minutes. The second test, conducted on the

4th of October, 2013, had a much higher initial concentration of E. coli, being 5.7×10^6 CFU/mL. The UVA irradiance of this day was lower than for the first test, with an average irradiance of 23 W/m^2, starting at approximately 25 W/m^2 and decreasing down to 21.5 W/m^2. Despite the higher initial concentration and lower UVA irradiance, the concentration of E. coli was below detectable limits after 22 minutes. This is more than a 5-log reduction in pathogens. These results of both tests are shown in Fig. 3, which plots the log reduction of the initial concentration against the UVA dose applied to the test volume. The UVA Dose (kJ/L) is the incoming solar power (UVA wavelengths only) (W/m^2) integrated over the exposure time (s) scaled for the size of CPC collector (m^2) and the volume of water treated (L). Despite marked differences in the incoming solar radiation and initial E. coli concentrations between the two test cases, the data collapses onto one curve. Figure 3 can therefore be used to estimate performance of the system or to establish design criteria based on known volume requirements and an expected insolation.
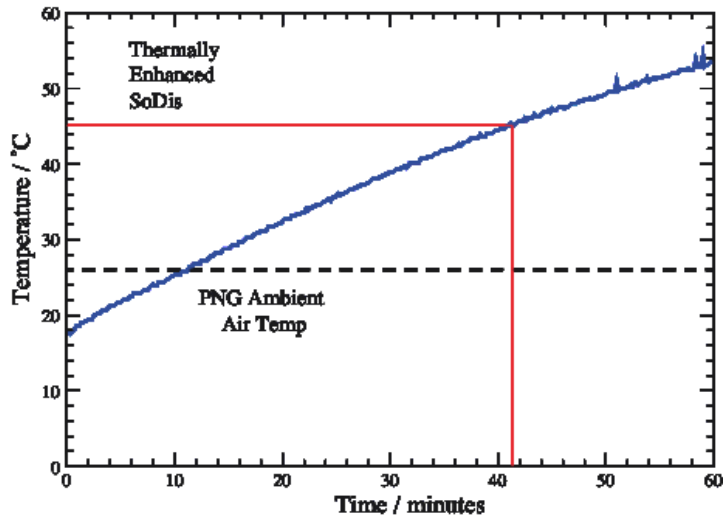

Figure 2. Temperature results for laboratory-based experiments of the manufactured system
with 1.25 litres of water, zero mass flow rate and a reactor tube at 0° inclination.

The rudimentary system was constructed from improvised materials, utilizing a flow through design across 3 CPC collectors in series. Rather than 33° orientation, which is optimal for Adelaide, each module was orientated at 10°, which is optimal for PNG. This ensures flow rate similarities to that expected in PNG, but provides an underestimate of UVA irradiance that can be expected in-country during actual operations. Contaminated water flowed from a feed reservoir through the three modules into a collection reservoir. The water was gravity feed, with the flow rate controlled by an in-line tap, with a flow rate of approximately 0.14 L/min.

During the experiment, water samples from the feed and collection reservoir, outlet water temperatures, flow rates and global radiation were taken every 30 minutes. UVA radiation was logged continuously. The water temperature was measured using an IR thermometer and not the LM335 sensors. During the testing, global radiation ranged from 841 W/m^2 to 1062 W/m^2 and UVA radiation ranged from 24 W/m^2 to 35 W/m^2. Maximum outlet water temperature was 37.1°C, compared with the reservoir temperature of 29°C. This indicates that thermally enhanced SoDis was not occurring.

The initial concentration of E. coli was 8×10^5 CFU/mL and the feed reservoir concentration of E. coli remained unchanged throughout the tests. The concentration of E. coli in the collection reservoir was below detectable limits. These preliminary results therefore show that this system successfully treats 34 Liters of water in 4 hours from an initial concentration of 8×10^5 CFU/mL to below detection limits. Considering the sub-optimal orientation, it can be expected that results in-country will be allow for a higher flow rate, and therefore more treated water. In fact, the rudimentary system at the tested flow rates provides a UVA dosage of over 5 kJ/L. Figure 3 would suggest that

approximately 50 L could be processed to below the detection limits under the same conditions, assuming that the improvised CPC offers similar performance to the manufactured system shown. The actual efficiency of a practical, improvised system compared with the workshop manufactured benchmark is future work currently underway.
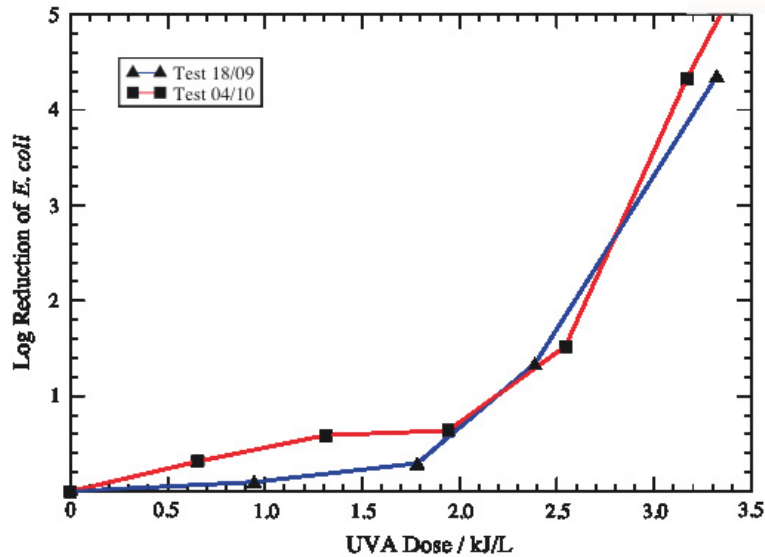

Fig. 3. Plots of E. coli concentration versus sunlight exposure time, with corresponding UVA dosage.
Results are for tests conducted on two separate days.

4. Conclusion

In order to increase the quality of water to the population of the rural mountains of PNG a gravity feed water treatment system that utilizes UVA radiation from the sun has been designed. The water treatment system can be easily made from simple materials including timber, glass tubes and metalized plastic and as it has no moving parts is easy to operate and maintain. Testing shows that a rudimentary system consisting of three modules can treat 34 Liters of water in 4 hours from an initial E. coli concentration of 8×10^5 CFU/mL to below detection limits. Another advantage of the system is that it can be scaled-up as necessary to meet the water processing requirements of each application.

Acknowledgements

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