Effectiveness of Solar Disinfection for Household Water Treatment

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PROJECT REPORT APPROVAL

The thesis titled "EFFECTIVENESS OF SOLAR DISINFECTION FOR HOUSEHOLD WATER TREATMENT" submitted by Md.Habibur Rahman Bejoy Khan and Md.Abu-Sa-Ad Akash with St. ID: 155408 and 155444 has been found as satisfactory and accepted as partial fulfillment of the requirement for the Degree, Bachelor of Science in Civil Engineering.

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DECLARATION OF CANDIDATE

We hereby declare that the undergraduate research work reported in this thesis has been performed by us under the supervision of Professor Dr. Md. Rezaul Karim and this work has not been submitted elsewhere for any purpose (except for publication).

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DEDICATION

We dedicate our thesis work to our family. A special feeling of gratitude to our loving parents. In addition, we express our deep gratitude towards our respected thesis supervisor Professor Dr. Md. Rezaul Karim

We also dedicate this thesis to our many friends who have supported us throughout the process. We will always appreciate what they have done.

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"In the name of Allah, Most Gracious, Most Merciful"

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ABSTRACT

Scarcity of water is one of the most important problems worldwide. The lack of freshwater and its dissimilar distribution together with inadequate sanitation and hygiene in low-income areas makes that nowadays millions of people are drinking contaminated water with fecal contamination. As a result, a number of waterborne pathogens present in this water induce serious diseases that, in many cases could be lethal in the most vulnerable population.

Solar disinfection (SODIS) is an environmentally sustainable, low cost and simple point-of-use (POU) household water treatment method which can eliminate the pathogen responsible for contaminating water in any remote areas without any careful guidance and recent studies show that they may implemented as an effective method of disinfection of microbiologically contaminated water.

In this study, an intensive assessment of effectiveness of solar disinfection under different seasonal variation in Bangladesh along with using different materials and modification are elaborated following the guidelines of WHO household water treatment methods. Escherichia coli (E. coli) spiked into sample water are put in different containers like polyethylene terephthalate (PET) bottles and plastic bag are exposed to solar irradiance by laying on corrugated steel sheet and aluminum foil paper. In summer season, a 5.4 log reduction using PET bottles are observed on corrugated steel sheet from 8hr exposure and regrowth of bacteria occurs after 12hr but in monsoon season since the weather is cloudy, a 4.22 log reduction using plastic bag for 16hr exposure are observed on aluminum foil paper laid on corrugated steel sheet. In

winter season, a 4.72 log reduction observed using plastic bag for 8hr exposure on same conditions and the regrowth prevails in all season. The physicochemical parameters of samples assessed did not show any variation with respect to the seasonal variation. Using plastic bag with foil paper laid on corrugated sheet is more effective in the inactivation of bacteria for all seasons. Furthermore, this study illustrates modelling of required time for 4-log inactivation of bacteria by using Weibull distribution model. In summer season, only 3 hours of SODIS could give highly protective water according to WHO guideline of HWT technologies and further in winter and monsoon season it takes less time of treatment by solar irradiance. However, the model also shows the acquired data from required experiments done fits well and the minimum and maximum irradiance of different seasons are shown and recommended the feasible way of solar disinfection.

CHAPTER ONE

INTRODUCTION

1.1 General

Lack of water and sanitation causes a great problem of microbiological contamination in water for human consumption. Drinking water contaminated by pathogens poses a huge threat to human health worldwide. This problem is specifically significant in developing countries like Bangladesh and is some arid areas where source of water is scarce. Surface waters such as rivers, streams and lakes are used by many locals for multiple purposes for instance livestock watering, bathing, cooking and even drinking in some areas in developing countries. Open defecation and urination often contaminated the nearby water source. In developing countries like Bangladesh people do not have other options for drinking water than pathogen contaminated water because of lack of water treatment systems and water distribution infrastructures.

According to the Sustainable Development Goal target 6.1 of the World Health Organization (WHO) calls for universal and equitable access to safe and affordable drinking water but in 2017 about 2.2 billion people globally lack access to safely managed drinking water services, among them 435 million people taking water from unprotected wells and springs and 144 million people collecting untreated surface water from lakes, ponds, rivers and streams ((WHO), 2019). Poor management of urban, industrial, and agricultural wastewater causes the contamination of drinking-water of hundreds of millions of people and their life in major stake. According to the World Health Organization (WHO) about 829000 people are estimated to die each year from

diarrhea as a result of unsafe drinking-water, sanitation, and hand hygiene and the death of 297000 children aged under 5 can be preventative if the risk factors are assessed ((WHO), 2019). Diarrhea is the most widely known disease which is linked to contamination of food and water but there are other hazards for instance in 2017, over 220 million people required preventative treatment for schistosomiasis which is an acute and chronic disease caused by parasitic worms contracted through exposure to infested water ((WHO), 2019).This dramatic scenario may worsen globally in the future, mostly due to climatic change and human demographic growth (United Nations, 2014) (McMichael AJ, 2006). . In according to the United Nations, about more than 20% of diarrheal cases could be prevented by introducing effective interventions to increase water quality at the distribution sources or point-of-use interventions within households (WHO, 2012). Household water treatment (HWT) interventions may play an important role in protecting public health where existing water sources, including those delivered via a piped network or other improved sources, are untreated, are not treated properly or become contaminated during distribution or storage (UNICEF & WHO, 2009). It is generally expected point-of-use (POU) treatment will be low cost, sustainable and easy to use in any worst case scenarios.

There are several HWT technologies that are being used for treating water. The available technologies are boiling, coagulation, sedimentation, chlorination, filtration, solar disinfection, uv-radiation or a combined form of one or more of these methods. Commonly these apparatuses are compiled and assembled in the country or imported from neighboring countries. In this study Solar disinfection (SODIS) were tested for bacterial removal efficiencies. Among different household water treatment methods, such as boiling, chlorination, and filtration, solar disinfection (SODIS) has been used in recent decades as a very cheap, clean, and simple method

for improving the microbial quality of drinking water in many developing countries (McGuigan KG, 2012) (Reed, 2004).HWT methods is given greater focus as a means of providing safe drinking water to consumers. Hence it is important to determine the most efficient means of point-of-use water treatment method. The bacteria removal efficiencies were analyzed by calculating the *Log Reduction Value (LRV)* of each option and application of Weibull distribution model was applied to determine the data fits.

The main goal of this work was to compare efficiency of SODIS for different seasons irradiance of sun following the guidelines of WHO (WHO, 2011) on different containers using different environmental condition along with experimental modifications.To verify the required duration of regrowth of microorganisms of the treated water and to focus on the estimation of the post irradiation behaviour.Lately,the Weibull models were verified as appropriate expressions of bacterial inactivation test (M. D. Stockera, 2014).Here, application of the Weibull models with the found data of different seasons solar disinfection ,required time of bacterial inactivation are given.To assess the best of our knowledge since solar disinfection in Bangladesh has been studied very less in so far.

1.2 Objective of the Study

The purpose of the study is to understand and have a proper knowledge about solar disinfection (SODIS) in Bangladesh along with variation of seasons. The specific objectives are:

- To assess the removal of pathogenic microorganism using SODIS under different environmental conditions.

- To verify the regrowth of microorganisms of the treated water.

- To apply a mathematical model to simulate the bacterial disinfection process using SODIS.

1.3 Scope of the study

There were several tasks that were required to be performed in order to accomplish the aforementioned objectives which are outlined below:

1. Setting up the required tools for conducting study according to WHO guideline for all of the treated water samples.
2. Measurement of bacterial removal and physicochemical parameters of all test waters.
3. Comparing the results between different environmental conditions along with different material type.

1.4 Thesis Layout

Chapter 1: This chapter includes a general introduction, background, objectives and scope of the study.

Chapter 2: This chapter consists of the literature review which covers water quality aspects and water borne diseases and problems caused by it. SODIS as a household water treatment technologies and related research studies are also discussed.

Chapter 3: Detailed methodology of all the experiments performed is discussed here. It includes the process by which the guideline had been followed while performing the relevant experiments. Details of scheduling, laboratory set up, spiking, taking measurements, sampling and analysis of the test samples from different options of water treatment.

Chapter 4: Results of the experiments that were performed are analyzed in this chapter. The microbiological and physicochemical parameters are also presented with relevant analysis. Comparison between different types of treatment environmental conditions is done.

Chapter 5: This chapter includes the conclusion from the experiments conducted for SODIS as a HWT technology options. It includes findings and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Solar Disinfection

Solar Disinfection (SODIS) is a simple, environmentally sustainable, low cost point-of-use (POU) solution for household drinking water dilemma from pathogen contaminated water for consumers and can be an effective solution to replenish the available diminishing volume of clean water and further replace the portion of clean water being contaminated on a continued basis (Jeelan S. Haddad, 2016).It is used in about more than 50 nations of Asia among million of people for disinfecting their water (McGuigan KG, 2012).Even places where have adequate supplies of water may not have access to microbiologically safe water, as improved supplies are often contaminated with pathogens that may cause infectious diseases, such as enteric fever and cholera (M.D. Sobsey, 2008).SODIS can be applied without any skilled supervision and enormous resource in any remote areas as the solar irradiance destroy the bacterial concentration in water. It required no commercial supply chain, as long as polyethylene terephthalate (PET) bottles are availale, and it has proved effective in significantly decreasing diarrhal diseases in children in developing countries (R.M. Conroy, 1996) (A.Rose, 2006).PET bottle may not cause any health risk and so are considered as safe,widespread availabe and adequate for SODIS application (M.T. Amin, 2009) as no indication for migration of possible photoproducts or additives from PET bottles into water was observed during sunlight treatment of water (M. Wegelin, 2001).

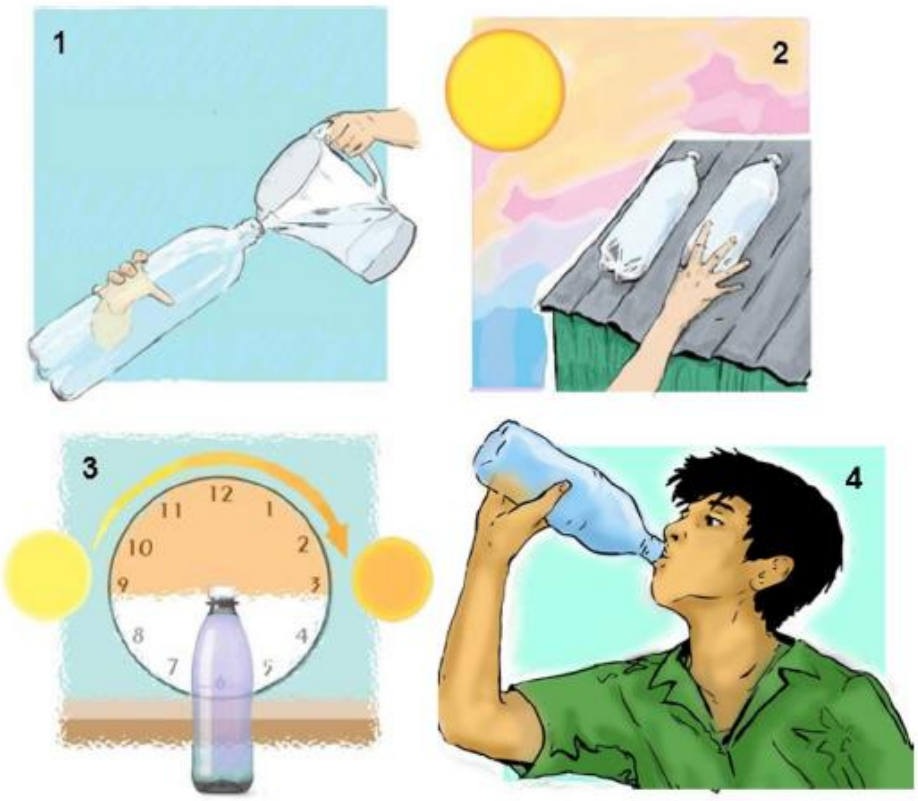

Figure 2. 1. Graphical representation of SODIS technique (McGuigan et al,2012)

Solar disinfection of water even reduce rate of morbidity in areas with inadequate sources of treating water or where some natural disaster has occurred (Conroy, 1996).Usually bottles made of PET are exposed to sunlight for one full day (6 hr of sunshine,including midday hours) or for two consecutive days under cloudy conditions (McGuigan KG, 2012).Solar disinfectin can converts the solar energy into heat to increase the water temperature for pasteurisation or distillation, or it can use directly the germicide effect of UV radiation (M. Boyle, 2008) or a combination of both.It is usually used as an alternative method in absence of proper treatment works (Reed, 2004).The treated water from solar disinfection is even said to cure stomach problems up to an appreciable extent (Rainey, 2005).Some of the SODIS works reviewed by McGuigan et al. (McGuigan KG, 2012) have demonstrated the ability of UVA and UVB wavelengths of the solar spectrum to inactivate a vast number of microorganisms such as Escherichia coli,Salmonella, Shigella Flexneri, Fusarium and more (Egli, 2006) (Cara-

GarcíabJ.C.Tellob, 2009) (M.I.Polo-LópezaP.Fernández-Ibáñeza et al,2011) (J.Ndounlaae et al, 2013).Turnished water is normally the main cause of illness resulting due to gastrointestinal problems which occurs usually in rural areas where resources of water are contaminated and poor sanitation exists (Caslake, 2004).SODIS being a cost effective method can be widely used in rural and camps of disaster areas to serve the mankind (McGuigan, 1998).However, apart from disinfecting effect SODIS there is no adequate amount of studies on the solar post-irradiation period.

Regrowth of bacteria has been assessed in some works as an indicator of the quality of disinfection(Angela et al,2007)(Angela et al, 2004) while some author also studied after the photo-treatment of water (Angela-GuiovanaRincónCesarPulgarin, 2007) (M. Inmaculada Polo-López a, 2012) and some monitored the survival in wastewater (FrançoiseBichai, 2012) and other water matrices (Stefanos Giannakis, 2014).The existence of nutirent sources in wastewater influence the growth potential for microorganisms , posing a direct threat by re-contamination of th ewater, so the prediction of the phenomenon should be assessed as well as the suggested pre-treatment conditons (Stefanos Giannakis, 2015).Furthermore, recent results of SODIS application suggests that this technology can be efficiently applied to different types of waters such as wastewater effluents for its regeneration (Sergio Gutiérrez-Alfaro, 2018).Due to the regrowth of pathogen after post-exposure of solar,it is recommended that SODIS water should be consumed within 24 hr (McGuigan KG, 2012).The efficiency of SODIS can increased by adopting different techniques such as- use of aluminium foils and mirros (Jeelan S. Haddad, 2016),painting the underside of the SODIS reactor black to enhance solar heating (B. Sommer, 1997),turbid water may be filtered and placing bottles on refracting surface (such as aluminium

or a roof made with corrugated iron sheets) (McGuigan KG, 2012) (Alexander S. Harding, 2012) (Heaselgrave & Kilvington, 2012).

2.2 Solar Radiation as a Disinfection Mechanism

For over 4000 years, sunlight has been used as an effective disinfectant (Conroy *et al.*, 1996). When organisms are exposed to sunlight, photosensitizers absorb photons of light in the UV-A and early visible wavelength regions of 320 to 450 nm. The photosensitizers react with oxygen molecules to produce highly reactive oxygen species. In turn, these species react with DNA; this leads to strand breakage, which is fatal, and base changes, which result in mutagenic effects such as blocks to replication. For bacteria, the process is reversible as the bacteria may again become viable if conditions allow cells to be repaired (Kehoe *et al.*, 2001; McGuigan *et al.*, 1999). Viruses are unable to repair DNA damage and are therefore sensitive to optical inactivation (McGuigan *et al.*, 2001).

SODIS uses two components of the sunlight for the water disinfection. The first, UV-A radiation has a germicidal effect. The second component, infrared radiation, raises the water temperature and is known as pasteurization when the water temperature is raised to 70°C- 75°C. The combined use of both UV-A radiation and heat produce a synergetic effect enhancing the efficiency of the process.

2.2.1 Effects of UV-radiation

Solar radiation can be divided into three ranges of wavelength: UV radiation, visible light and infrared radiation.

UV radiation cannot be perceived by the human eye. It is a very aggressive radiation that can cause severe damage to the skin and eyes and destroys living cells. Luckily most of the UV-C and UV-B light in the range of 200 to 320 nm is absorbed by the ozone (O3) layer in the atmosphere which protects the earth from radiation coming from space. Only a higher fraction of UV-A radiation in the wavelength range of 320nm – 400nm, near the visible violet light, reaches the surface of the earth. UV-A light has a lethal effect on human pathogens present in water. These pathogens are not well adapted to aggressive environmental conditions as they fi nd their specific living conditions in the human gastrointestinal tract. Therefore, they are more sensitive to sunlight than organisms commonly abundant in the environment. UV-A radiation directly interacts with the DNA, nucleic acids and enzymes of the living cells, changes the molecular structure and leads to cell death. UV radiation also reacts with oxygen dissolved in the water and produces highly reactive forms of oxygen (oxygen free radicals and hydrogen peroxides). These reactive molecules also interfere with cell structures and kill the pathogens.

The first evidence of the bactericidal effect of sunlight was reported by Downes and Blunt in 1877 [Downes and Blunt, 1877]. It is commonly attributed to the synergistic effect of solar UV photons and mild-thermal heating produced during solar exposure. Nevertheless, each UV range may generate different injuries into cells according to their wavelength, as represented in Figure 2.

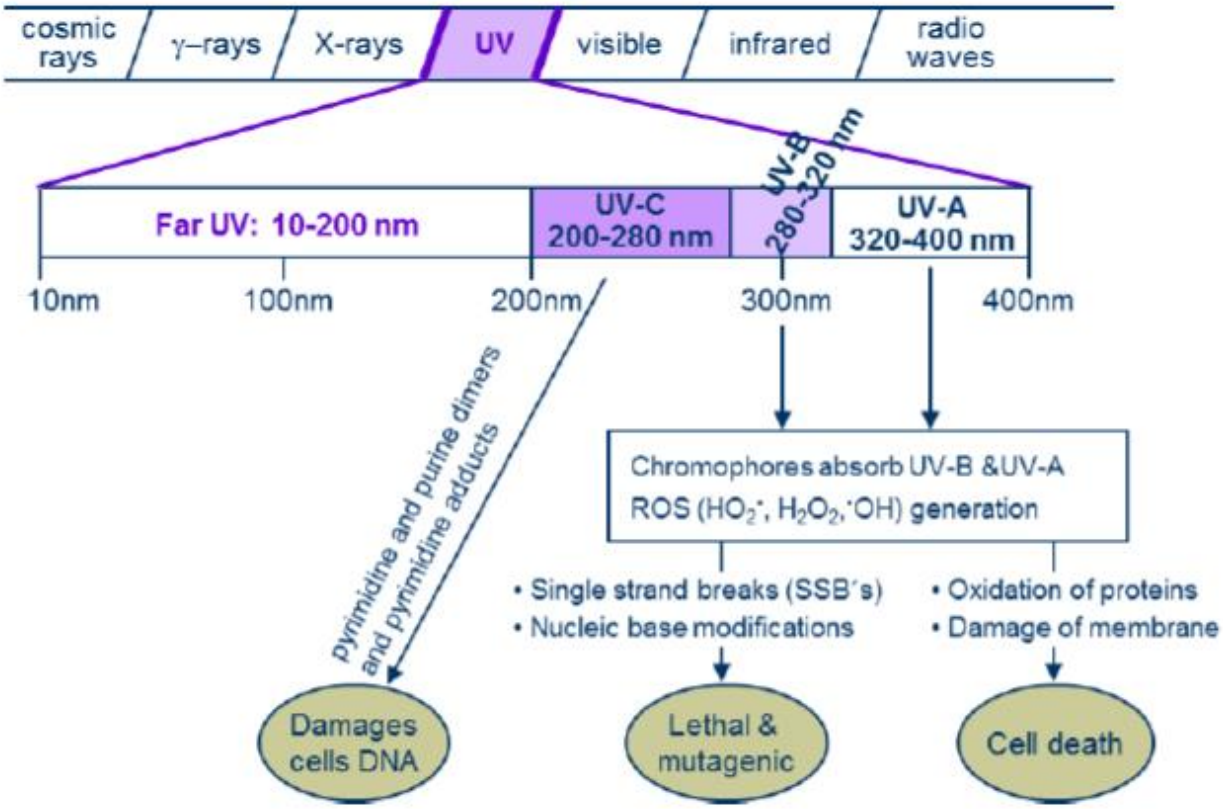

Figure 2. 2. Main damages in cells caused by UV radiations [Malato *et al.*, 2009]

2.2.2 Effects of temperature

Several factors affect the efficiency of disinfection by SODIS, lengthening or shortening the required solar exposure time to achieve a certain log-reduction. Solar irradiance and energy dose, wavelength, water temperature during treatment, water turbidity, salt concentration, dissolved oxygen, dissolved organic matter in the contaminated water and nature of the microorganisms are the most important factors that alter SODIS efficiency [Webb and Brown, 1979; Moss and Smith, 1981; Reed, 1997; McGuigan *et al.*, 1998; Ubomba-Jaswa *et al.*, 2009a; Ubomba-Jaswa *et al.*, 2010]. Regarding the temperature effect, Solic and Krstulovic studied the separated and combined effect of solar radiation and temperature on the survival of fecal coliforms in seawater [Solic and Krstulovic, 1992]. However, a beneficial effect at a threshold water temperature of 50 ^{o}C was observed, since at this temperature or above, the required fluences to inactive *E. coli* were

three times smaller compared to lower water temperatures [Wegelin *et al*., 1994]. To support these results, Berney and co-workers studied the thermal effect on *E. coli* in the dark and observed at slight rate of inactivation even at 48 ºC [Berney *et al*., 2006b]. Due to this strong synergy, a number of enhancement methods have been proposed to reach this water temperature value for SODIS acceleration. Some techniques used for increasing the water temperature are: (i) to use black paint over some sections of the bottles; (ii) to use absorptive materials, (iii) to circulate the water over a black surface in an enclosed container transparent to UVA light; (iv) to use solar collectors or solar reflectors [McGuigan *et al.*, 2012].

Another aspect of the sunlight is the long-wave radiation called infrared. Also this radiation cannot be seen by the human eye, but we can feel the heat produced by light of the wavelength beyond 700nm . The infrared radiation absorbed by the water is responsible for heating it up.

Table 2. 1. Thermoresistance of microorganisms [Feachem R. et al ,1983]

Microorganisms	Temperature for 100 % Destruction		
	1 Min.	6 Min.	60 Min.
Enteroviruses			62 °C
Rotaviruses			63 °C for 30 Min.
Faecal Coliforms	at 80 °C complete destruction		
Salmonellae		62 °C	58 °C
Shigella		61 °C	54 °C
Vibrio Cholera			45 °C
Entamoeba Histolytica Cysts	57 °C	54 °C	50 °C
Giardia Cysts	57 °C	54 °C	50 °C
Hookworm Eggs and Larvae		62 °C	51 °C
Ascaris Eggs	68 °C	62 °C	57 °C
Schistosomas Eggs	60 °C	55 °C	50 °C
Taenia Eggs	65 °C	57 °C	51 °C

Microorganisms are sensitive to heat. The table 1 lists the temperature and exposure time required to eliminate microorganisms. It can be seen that water does not have to be boiled in order to kill 99.9% of the microorganisms. Heating up the water to 50-60°C for one hour has the same effect.

2.2.3 Synergetic effect of UV-A radiation and temperature

At a water temperature of 30°C, a fluence of 555 W*h/m2 (350-450 nm, dose of solar radiation corresponding to approximately 6 hours of mid-latitude midday summer sunshine) is required to achieve a 3-log reduction of faecal coliforms. Under these conditions, only the effect of UV-A radiation is present (Wegelin M. et al ,1994).

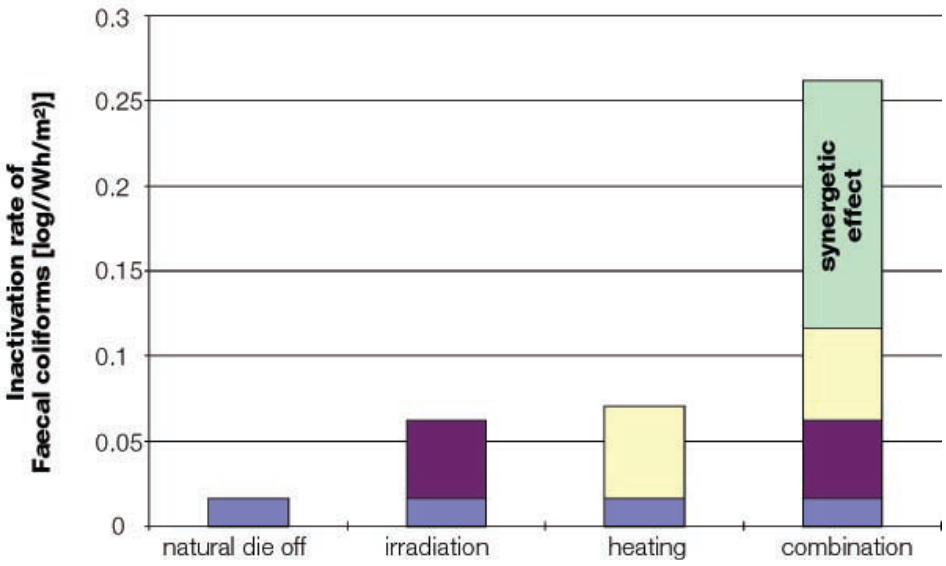

Figure 2. 3. Synergetic effect of UV-radiation and temperature on Faecal coliforms in raw water (Wegelin M.et al ,1994).

However, the die off rate of faecal coliforms exposed to sunlight increases significantly, when 2 stress factors, UV-A radiation and increased water temperature are present. At a water temperature of 50°C, a synergetic effect of UV-A radiation and temperature occurs: a 3-log reduction of faecal coliforms only requires a fluence of 140 W*h/m2. This is equivalent to an exposure time of only one hour (Wegelin M. et al ,1994).

2.3 Effect of SODIS on pathogens

Human pathogens are adapted to live in the human intestines, where they fi nd a dark, humid environment and temperatures ranging between 36°C and 37°C. Once the pathogens are discharged into the environment, they are very sensitive to the harsh conditions outside the human body. They are not able to resist increased temperatures and they do not have any protection mechanisms against UV radiation. Therefore, temperature and UV radiation can be used to inactivate the pathogens.

Research has shown that pathogenic bacteria and viruses are destroyed by SODIS. The inactivation of the following microorganisms has been documented:

- Bacteria: Escherichia coli (E. coli), Vibrio cholerae, Streptococcus faecalis, Pseudomonas aerugenosa, Shigella fl exneri, Salmonella typhii, Salmonella enteritidis, Salmonella paratyphi [Acra A. et al,1984/Wegelin M.,1994/Sommer B.et al ,1997]
- Viruses: Bacteriophage f2, Rotavirus, Encephalomyocarditis virus [Wegelin M.,1994]
- Yeast and Mold: Aspergillus niger, Aspergillus flavus, Candida, Geotrichum [Acra A.et al,1984]

However, the inactivation of spore and cyst forming organisms such as protozoa; Entamoeba hystolitica, Giardia intestinalis, Cryptosporidium parvum and helminths by solar water disinfection has not systematically been assessed yet.

These organisms can be destroyed by using temperature (boiling, pasteurization). Microorganisms have a specific sensitivity to heat. The thermal death point of amoebic and Giardia cysts is at 57°C (during 1 Minute exposure, see Table 1 on Thermoresistance of microorganisms). SODIS will effectively destroy these pathogens if the water in the exposed

SODIS bottles reaches a temperature of 57°C for 1 Minute or if the contaminated water maintains a temperature of 50°C during an hour.

Most human pathogens are very fragile, cannot multiply and die outside the human body. One of the few exceptions is salmonella, which however requires favorable environmental conditions (e.g. appropriate supply of nutrients) to survive. It is important to note that SODIS does not produce sterile water. Organisms other than human pathogens such as for example Algae, are well adapted to the environmental conditions in the SODIS bottle and may even grow there. These organisms however do not pose a danger to human health. As SODIS does not produce sterile water, it is necessary to use adequate parameters to assess its efficiency.

2.3.1 Indicators used to test the efficiency of SODIS

Many waterborne pathogens can be detected directly but require complicated and expensive analytical methods. Instead of directly measuring pathogens, it is easier to use indicator organisms indicating fecal pollution in the water. A fecal indicator organism has to meet the following criteria:

• It is present in high number in human feces,

• It is detectable by simple methods,

• It does not grow in natural waters,

• It's persistence in water and it's removal by the water treatment method is similar to the water-borne pathogens.

Many of these criteria are fulfilled by Escherichia coli (E. coli, fecal coliform). E. coli is therefore a good indicator organism to assess fecal contamination of drinking water if the

resources for microbiological examination are limited [WHO,1993]. An important point is, that testing for E. coli is also possible under difficult field conditions in a developing country, for example by using the portable DelAgua field test kit (http://www.eihms.surrey.ac.uk/robens/env/delagua.htm).

Some organisms such as Enteroviruses, Cryptosporidium, Giardia and Amoebae however are more resistant than E. coli. The absence of E. coli therefore does not necessarily indicate their removal. Spores of sulfite-reducing Clostridia can be used as an indicator for these organisms [WHO,1993]. But such analytical methods cannot be used for routine tests under field conditions as they are time-consuming and expensive.

Total coliform bacteria cannot be used as an indicator for the sanitary quality of untreated raw water, as they are naturally abundant in the environment.

Neither is the total count of bacteria an adequate parameter for the assessment of SODIS efficiency, as harmless organisms, such as for example environmental bacteria or Algae, may grow during sunlight exposure of a SODIS bottle.

2.4 SODIS efficiency

SODIS efficiency was systematically tested for different pathogens, using different water qualities, various types of containers and under different climatic conditions. Field tests are performed to confirmed the results from laboratory research. Here some of the conditions of efficiency are shortly evaluated.

2.4.1 Physicochemical water quality

Turbidity

Raw water used for SODIS should be as clear as possible. However, field tests reveal that turbid water up to 30 NTU may be treated with SODIS under normal climatic conditions. Water of higher turbidity needs to be pretreated (Sommer B. et al ,1997/Reed R.H.,1997).

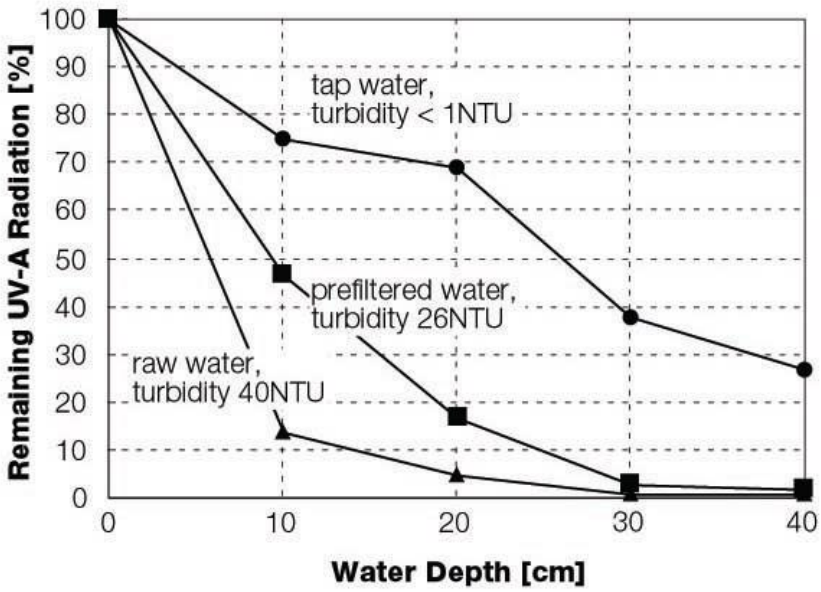

Figure 2. 4 Reduction of UV-A radiation as a function of water depth and turbidity (Sommer B.et al,1997)

Oxygen

Laboratory research showed that inactivation of bacteria (*E. coli, Enterococcus faecalis, Streptococcus faecalis*, faecal coliforms) is much more efficient in aerobic than in anaerobic conditions. Field tests confirmed that the shaking of bottles enhances SODIS efficiency, but suggest that the effect is smaller than assumed by laboratory research.

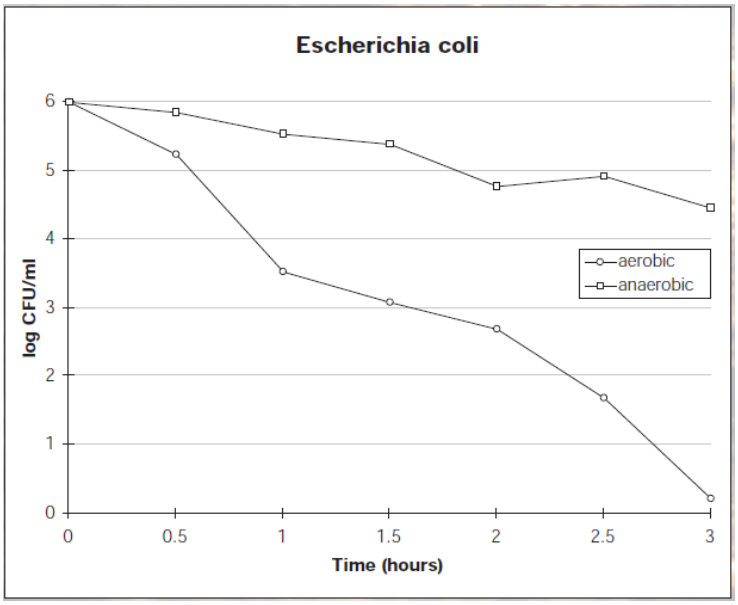

Figure 2. 5. Inactivation of E.coli under aerobic and anaerobic conditions (Reed R.H.,1997)

It is recommended to shake ¾-filled bottles for about 20 seconds before filling them completely. Especially stagnant water of low oxygen content drawn from ponds, cisterns and wells should be aerated before sunlight exposure (Quispe V. et al,2000/Reed R.H.,1997/Reed R.H.,1997).

Color

Tests have shown that high levels of color in the water increase the time required for inactivating the pathogens (Reed R.H.,1997).

2.4.2 Microbiological water quality

Fecal coliforms

Most laboratory and field tests have been carried out with *Escherichia coli* bacteria or with faecal coliforms (a group of faecal bacteria that include *E. coli*). Under normal conditions, the disinfection process shows an efficiency level of about 3 logarithms (99,9%) (Wegelin M.,1994/Sommer B.et al,1997/Quispe V. et al,2000).

Vibrio cholerae

Inactivation rates for *V. cholerae* are similar to the ones for faecal coliforms with water temperature > 50°C. If the threshold temperature of 50°C is not reached, ***V.*** *cholerae* shows higher inactivation rates than faecal coliforms (Sommer B.et al,1997/Solarte Y.et al,1997).

Parasites

Laboratory tests suggest that *Giardia (G. lamblia, G muris*), a very common water-borne parasite, is susceptible to sunlight. Another parasite, *Cryptosporidium parvum,* seems to be more resistant. However, it is worth to note that *C. parvum* is also very resistant to chlorine (Lawand T.A,1988/Zerbini C.,1999). Field tests are currently carried out with both parasites.

2.4.3 Containers support

Plastic Bottles

Field tests show that transparent PET bottles of 2 liters volume are very appropriate containers for SODIS. Tests show good results for both returnable and one-way bottles, however one-way bottles are slightly better as they transmit more UV radiation. The effect of aging does not significantly affect the transmission coefficient of one way bottles.

Coloured bottles do not transmit enough UV radiation; these bottles should not be used for SODIS (Wegelin M.,2000/Quispe V.,2000).

Glass bottles

Transparent glass bottles theoretically may also be used as an alternative to plastic bottles. However, glass with a higher content of iron oxide transmits less UV-A radiation. Field tests confirm that certain glass bottles show lower disinfection rates. Furthermore, glass bottles frequently break. Therefore, glass bottles are not recommended (Lawand T.A.,1988/Sommer B. et al,1997/CASA/UMSS,1997).

SODIS bag

Especially developed SODIS plastic bags show higher efficiency due to a better surface-volume ratio, but they are not recommended as they are not available locally, are difficult to handle**,** break faster than plastic bottles (Sommer B.et al,1997, SODIS News No.1, SODIS News No.3).

Plastic bag

Locally available transparent polyethylene plastic bags have been tested and show a very high disinfection efficiency, but are not recommended for the same practical considerations as described for the SODIS bag (CASA/UMSS,1997).

Bottle support

A similar temperature increase may be obtained with the use of CGI-sheet as support for water bottles. Other dark support are also suitable (Sommer B.et al,1997/Quispe V. et al,2000)

2.4.3 Influence of weather conditions

Cloudy sky

With covered sky conditions, it is possible that the UV dose received during one day of exposure will not be sufficient to achieve a satisfactory water quality. Laboratory tests realized with viruses showed that the radiation dose is cumulative and that two consecutive days of exposure may be sufficient to inactivate the pathogens. This data still needs to be confirmed under natural conditions and for other pathogens, especially bacteria (Wegelin M. et al ,1994/Sommer B.et al ,1997).

Parameters affecting water temperature

Air temperature and wind are the two climatic factors influencing the water temperature, which has a direct impact on the efficiency of the process. However, field test carried out in the north-west plateau in China and in the highlands of Bolivia reveal that countries with cold/temperate climates are also suitable for SODIS, provided sufficient solar radiation is available (Quispe V.et al,2000/CASA/UMSS,1997).

2.5 Health benefits of SODIS

Solar water disinfection (SODIS) provides an unusually simple, efficient and sustainable drinking water treatment option. Thus it reduces health risks associated with the consumption of contaminated drinking water.

Type of diseases reduced by SODIS

SODIS affects pathogens present in the drinking water and therewith reduces the occurrence of enteric diseases caused by these pathogens:

- **infectious diarrhoea**

from bacterial infections with enteropathogenic *Escherichia coli*

- **dysentery**

watery diarrhoea from bacterial infections with Salmonella or Shigella

- **dysentery**

from parasitic infection with *Giardia lamblia* (“Giardiasis”) or *Entamoeba hystolytica* (“Amoebiasis”)

- **cholera**

from bacterial infection with *Vibrio cholera*

A number of viral agents such as rotavirus and adenovirus are responsible for a large burden of viral gastroenteritis, however, routes of infection other than through drinking water dominate virus transmission and infection (person-to-person, droplets).

2.6 Advantages of SODIS

SODIS improves the microbiological quality of drinking

water. SODIS improves the family health. SODIS can serve as an entry point for health and hygiene education. Public water supply systems in developing countries often fail to provide water safe for consumption. SODIS provides individual users a simple method that can be applied at household level under their own control and responsibility. SODIS is easy to understand. Everybody can afford SODIS, as the only resources required are sunlight, which is cost free and plastic bottles. SODIS does not require a large and costly infrastructure

and therefore easily is replicable in self-help projects. SODIS reduces the need for traditional energy sources such as firewood and kerosene/gas. Consequently, the use of SODIS reduces deforestation, a major environmental problem in most developing countries, and SODIS decreases air pollution created by burning conventional energy sources. Women and children often spend much of their time and energy collecting firewood. SODIS reduces this workload as less firewood needs to be collected. Financial advantages: Household expenditures can be reduced when the user's family health is improved: less financial resources are required for medical care. In addition, expenses for traditional energy sources such as gas, kerosene and

firewood are reduced. Only limited resources are required for the procurement of transparent plastic bottles. Therefore, even the poorest can afford SODIS.

2.6 Limitations of SODIS

There are several limitations to using solar disinfection to treat drinking water. The process of solar disinfection is best suited for regions having approximately 300 sunny days with clear skies each year, with areas between latitudes 35°N and 35°S having the optimum exposure of sunlight (Acra *et al.*, 1984; IDRC, 1998). However, any amount of cloud coverage reduces the intensity of sunlight that reaches the earth, thereby decreasing its germicidal effects. Despite this restriction, Acra *et al.* (1984) state that a longer exposure time more than compensates for the reduction in solar intensity.

Another difficulty presented with solar disinfection is that the materials needed for the process may not be readily available. Clear, cylindrical bottles are most effective at allowing solar radiation to reach the water, yet these may be difficult to obtain for largescale use by remote communities, where plastic containers are not sold. In addition, enhancements used by various researchers, such as foil (Kehoe *et al.*, 2001), may be difficult to purchase. Devices such as solar panels, copper piping, and thermostat valves were required to construct the solar panel described by Jorgensen *et al.* (1998) to pasteurize drinking water. Because these materials are not readily available in many less developed areas, and knowledge of constructing a solar water heater is not widespread, this method of heating water for large-scale use is impractical in developing countries. However, small-scale individual use of plastic bottles is a treatment method that can be implemented with minimal resources and little training.

CHAPTER THREE

METHODOLOGY

3.1 General

The experiments conducted for testing SODIS methods for different seasons in Bangladesh in the IUT Environmental Laboratory. Each of the experiments were performed following the World Health Organization guideline for drinking water. This chapter describes in details the different methodologies and procedures were conducted in performing the experiments.

3.2 Escherichia Coli (E. coli) culture and spiking

E. coli was prepared in the same way for determining efficiencies of different HWT technologies tested in the experiment. The *E. coli* used throughout the experiment was obtained from Environmental Microbiology Laboratory of International Centre for Dirrheal Disease Research, Bangladesh (icddr,b), Dhaka. In order to check the count of 5×10^6 CFU per 100 ml to have same count like Mwabi et el (2013) we have applied the serial dilution process for 5 times by streak plating each diluted samples on mTEC agar medium. The sample strain was sub-cultured using MacConkey agar. The prepared culture was incubated at 37°C for 24 hours. Colonies were isolated and sub-cultured in mTEC agar medium. Then it was incubated at 37°C for 2 hours and followed by 44°C for 18 – 24 hours. One step and one medium method using modified mTEC

agar was used for differentiation and enumeration of E. coli. This method was recommended by method 1603 published by the EPA in 2002. [dll version method 1603: E. Coli].

A fresh culture of E. coli ATCC 25922 that were grown on mTEC agar over night was used to prepare a suspension of E. coli in normal saline. Using drop plate technique 100 µl of diluted suspension was cultured. The E. coli was measured and found to be in the range of 10^6-10^7 CFU/100 ml. The saline was stored at around -15°C and before spiking they were placed in water bath in order to lower the temperature of the saline to room temperature. Spiking of E. coli was done in an air tight situation.

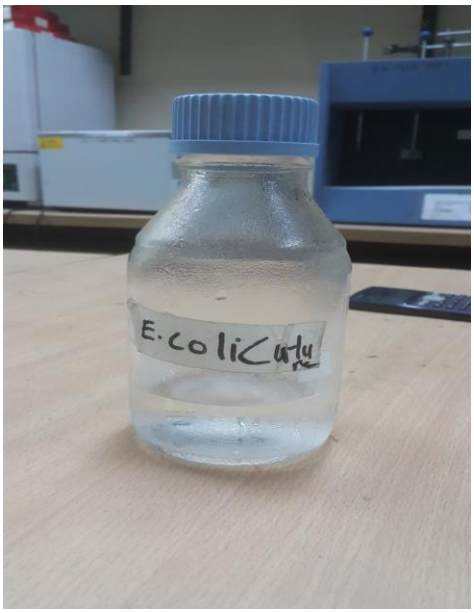

Figure 3. 1. E. coli culture in bottle.

Figure 3. 2.Spiking of E.coli in air tight situation.

3.3 Containers

500 ml containers made of transparent plastic polymer bag and polyethylene terephthalate (PET) and containing bottled water were purchased locally and were produced by Aquafina and Kinley. Plastic polymer bag were obtained locally from shops of Hatkhola at Motijheel. Labels of bottles were removed to get enough transmittance of UV-visible light. Purchased PET bottle is sterile since mineral water is kept by destroying all the pathogens in the bottle and plastic bag is sterilized with ethanol 75%. Both the containers are made sure that the UV-ray is fully transmittance and used properly while doing the experiment.

3.4 Test waters

According to WHO guideline for drinking water two types of water should be used for control experiments of HWT technologies.

Table 3.1.WHO guideline of drinking water for HWT technologies

	Test Water 1	**Test Water 2**
Description	High-quality groundwater, surface water, caught (newly harvested) rainwater or other water free of disinfectant residual	High-quality groundwater, surface water, rainwater or other water free of disinfectant residual with 20% by volume primary wastewater effluent or 1% by volume untreated raw sewage, sterilized or pasteurized.
Turbidity	< 5 NTU	> 30 NTU
pH	7.0-9.0	6.0-10.0
Temperature	20°C ± 5°C	4°C ± 1°C

The following figure shows how the test waters were prepared and further details on the preparation of these waters is provided below.

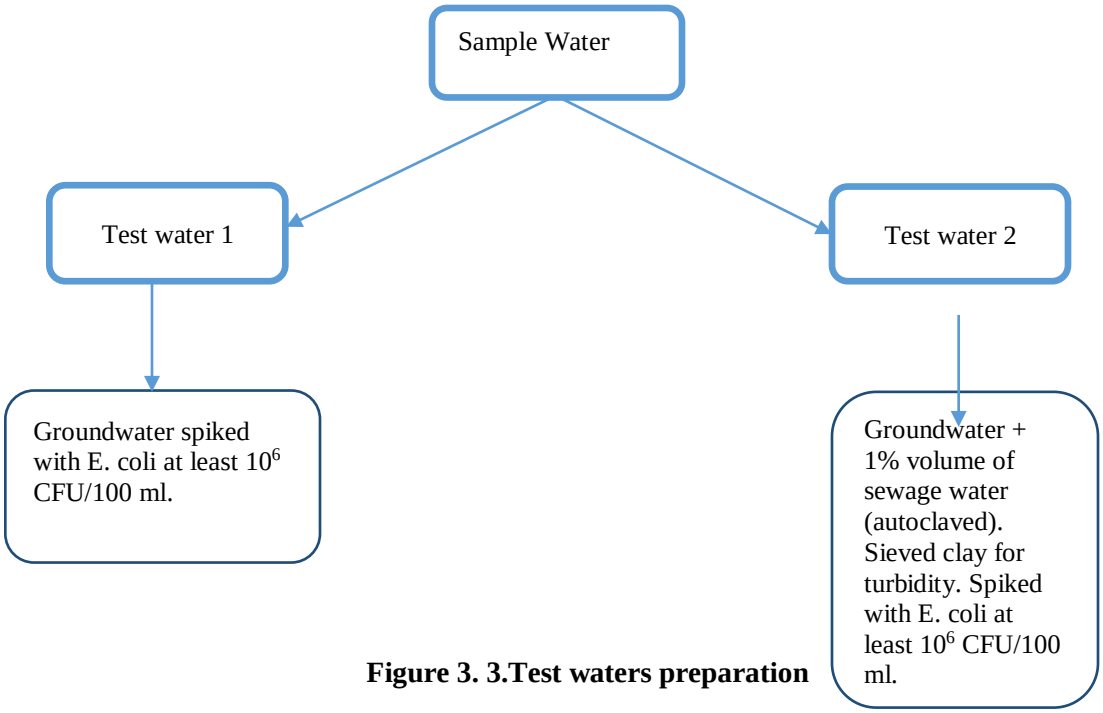

Figure 3. 3.Test waters preparation

Steps of preparation of the two types of test waters are shown below.

Test water 1 :

Water is supplied in IUT by means of a piped system with groundwater as the source. For the experiment, water was collected from taps in the laboratory and then they were spiked with E.coli bacteria by ensuring a count of 10^6 CFU/100 ml.

Test water 2:

Tap water is mixed with 1% by volume of autoclaved sewage water according to WHO guideline for drinking water. Type 2 water requires a turbidity of more than 30 NTU which is incorporated into the water by adding sieved clay. It is then spiked with 10^6 CFU/100 ml of E. coli bacteria.

3.4.1 Sample preparation

Two water containers of 10 L were washed, rinsed with sterile distilled water and sterilized with absolute ethanol prior to each experiment. Two sample water (test water-1 and test water-2) were prepared from the lab tap water of Islamic University of Technology in two 10 L containers according to WHO guidelines (WHO, 2011).The required test waters were evaluated by following ways.

Turbidity:

Clay is used to instill turbidity in the water sample. This clay taken from a sample of undisturbed soil sample of Dhaka-Chittagong highway in the Geotechnical Laboratory. The sample was obtained from below 30 m. This sample was sieved in a 200 mm sieve [ASTM. *ASTM D 6913 – 04 (2009)]* to obtain clay.

Sewage water:

Water was collected from raw sewage line and then autoclaved for 24 hours for sterilization. One percent by volume was then used for different filters during the experiment. (WHO)

E. coli:

The E. coli strain was obtained from the International Centre for Diarrheal Disease Research Bangladesh (ICDDRB) which was cultured on mTEC medium by streak plate procedure. One loop of E. coli was mixed in sterilized .85% normal saline (pH: 7.8-8.0) of 500 ml and well shaken in order to obtain the initial concentration that were spiked into the sample water. Then the E. coli solution was stored under 4^0 C. The concentration of E. coli in this solution is 2.2 X 10^8 CFU/100 ml.

Figure 3. 4.Test water-1 and Test water-2 prepared in PET bottle and plastic bag.

3.5 Sunlight exposure

Test waters were irradiated on a corrugated steel sheet platform on the roof of the parking lot of Islamic University of Technology in Gazipur, Bangladesh (latitude longitude).Containers were exposed on a tin sheet of South-facing include at an angle of 60˚.Containers were shaken before exposure and left undisturbed during all experiments, with an air space of about 15% of containers volume to allow for air circulation to achieve aeration (R.H. Reed, (1997)). Containers were typically exposed from 9 AM (+/- 30 min) to 5 PM for a total of 8 hour exposure. Solar irradiance and temperature were measured at an 1min interval throughout all experiments with a Solar Survey 200R Pyranometer (Seward Group,UK) where data are stored in the device data logger.

3.6 Experimental design

Bottle and plastic bag material experiments were conducted by simultaneously exposing 8 containers of test water-1 and test water-2, for a total of 16 containers per trial, as shown in Fig 1. In Summer and Winter season,8hr exposure experiments were conducted where each containers of different sample water were taken out at every 1hour exposure of solar irradiance

to test in the laboratory. But in Rainy season, the weather were cloudy and the solar irradiance were irregular and so 16hr exposure experiments were conducted for both sample waters. In order to improve the performance of bacterial inactivation aluminum foil paper were laid on the corrugated steel sheet platform in Rainy season and Winter season(Fig.1.).Replicate trials were performed for each conditions for different seasons of Bangladesh

Figure 3. 5. Diagram showing the test water samples to direct sunlight at rooftop in SODIS system.

3.7 Bacterial sample analysis

Sampling were done after each hour exposure of solar irradiance in Summer and Winter season but in Rainy season, it was done after 8 hour exposure respectively. The samples were always kept in sterile beaker in order to ensure their sterile preservation. For each experiments, 16 times sampling were done for both test waters for assessing the bacterial inactivation and the 8^{th} hour solar exposed container were sampled for 12 times in 1hr interval and 1times after 24hr in order to monitor the post irradiation time ,to measure survival and regrowth of the bacterial population (Stefanos Giannakis, 2015). 10 ml of each sample was filtered through filter papers having pores of 0.45 µm (Sartorious Stedim, Gottingen, Germany). After filtration the filter paper was placed

in a broth made from m-TEC produced in a petri dish. This was then placed in an incubator at 37°C for 24 hours. *E .coli* colonies have a characteristic white-greyish color which makes it possible to count the total number of colonies with the naked eye. Following the incubation period total number of colonies of *E. coli* is counted and recorded for each of the samples. USEPA Membrane Filtration (MF) method were used by the above ways to estimate the sampling of bacterial population using mTEC agar in a glass made petri dish.

3.8 Analytical methods

Four physic-chemical parameters of the analytical methods namely pH, turbidity, DO and electric conductivity were measured for both feed and filtered water. Also the temperature of the laboratory was tried to maintain according to the field condition. The following methods were used to evaluate these parameters.

pH

pH was measured by a calibrated HACH® pH meter (HACH sensION^{+} PH31).

Turbidity

Turbidity measurement was performed using proprietary nephelometric instrument. Turbidity is expressed as Nephelometric Turbidity Units (NTU). The apparatus used for turbidity evaluation is HACH® series portable turbidimeter (HACH 2100Q).

DO

DO was tested using a calibrated HACH® probe (HACH HQ 40D). Dissolved oxygen is expressed as mili-gram/liter.

Electric Conductivity

Electric conductivity was tested using a calibrated HACH® conductivity probe (HACH CDC40101). Electric conductivity is expressed as micro-siemens/cm (μs/cm)

3.9 Modelling of bacterial disinfection

To find out the bacterial response under the solar irradiance , the GInaFiT freeware add-on for Microsoft Excel was used (A.H. Geeraerd, 25 June 2005).From all the models tested and did the curves ; Model: The Weibull frequency distribution model (P.Mafart, January 2002) were used as they yielded R^2 close to 1 , the smallest RMSE and their calculation was possible for all the cases we applied.

3.9.1 Weibull inactivation model

The Weibull model is the Mafart suggestion to adapt the cumulative probability density function to microbial inactivation (P.Mafart, January 2002). The effort is ‘‘to reduce naturally’’ the classic log-linear model, and is as follows:

$$\frac{N}{N_0} = 10^{\left(-\left(t/\delta\right)^p\right)} \quad (1)$$

For identification purposes reformulated as:

$$\log_{10} N = \log_{10} N_0 - \left(t/\delta\right)^p \quad (2)$$

Where:

N: the (residual) bacterial population at any given time (CFU/mL).

N0: the initial bacterial population (CFU/mL).

t: the investigated time (s).

d and p: Weibull model-specific constraints (scale and shape parameters).

d is a scale parameter and marks the time for the first decimal reduction. For $p < 1$ concave curves are described and $p > 1$ describes convex shapes. Finally, d and p are not independent; there is a strong correlation existing, as suggested by Van Boekel (Boekel, 25 March 2002) and Mafart et al. (P.Mafart, January 2002), and is due to the model structure (Stefanos Giannakis, 2015).

3.10 Statistical analysis

The Microsoft Excel® Ver. 16.1 (Microsoft Corporation, Redmond, WA, USA) software packages were used for the evaluation of microbial analysis and effectiveness between different materials. In order to test the significance of the data set, a paired t-test were performed between aluminum foil paper and corrugated steel sheet dataset and between PET bottle and plastic bag

dataset. An ANOVA test were also performed between seasonal variation dataset. A significance level of 5% was used as a standard in the hypothesis tests, (Clark, 1974) while in all tests a p-value of <0.05 was considered statistically significant. The log reduction after SODIS treatment was calculated using equation (3).

$$\text{Log reduction} = \text{Log}_{10}\text{bacterial count}_{\text{beforetreatment}} - \text{Log}_{10}\text{bacterial count}_{\text{aftertreatment}} \quad (3)$$

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 General

The experiments conducted in laboratory were performed by following the guideline of WHO for HWT technologies. In this study, in order to check the effectiveness of SODIS in three season in Bangladesh i.e. Summer, Monsoon and Winter the experiments were conducted respectively. Different modification of experiments was performed for instance using foil paper on corrugated steel sheet, different duration of solar exposure in cloudy weather etc. PET bottle and plastic bag were used as containers in this study. Standard procedure was followed for testing solar irradiance and different physicochemical parameters. The results of these experiments are outlined in this section followed by conclusion based on WHO guideline.

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4.2 Analysis of physicochemical parameters

The physicochemical parameters which are DO, turbidity, electrical conductivity and pH are determined for the test waters on the basis of seasons in Bangladesh. Groundwater was used as a source of the water which we used throughout the experiment as feed water. It is a good source of mineral content with low organic content. However, the added wastewater can add colloidal and organic substance which causes variations in the physic-chemical parameters. There wasn't any change in physicochemical parameters for the seasonal variation. The physicochemical data

obtained in Summer season have been reported in Appendix A. Now the graphs for the physicochemical data are given following.

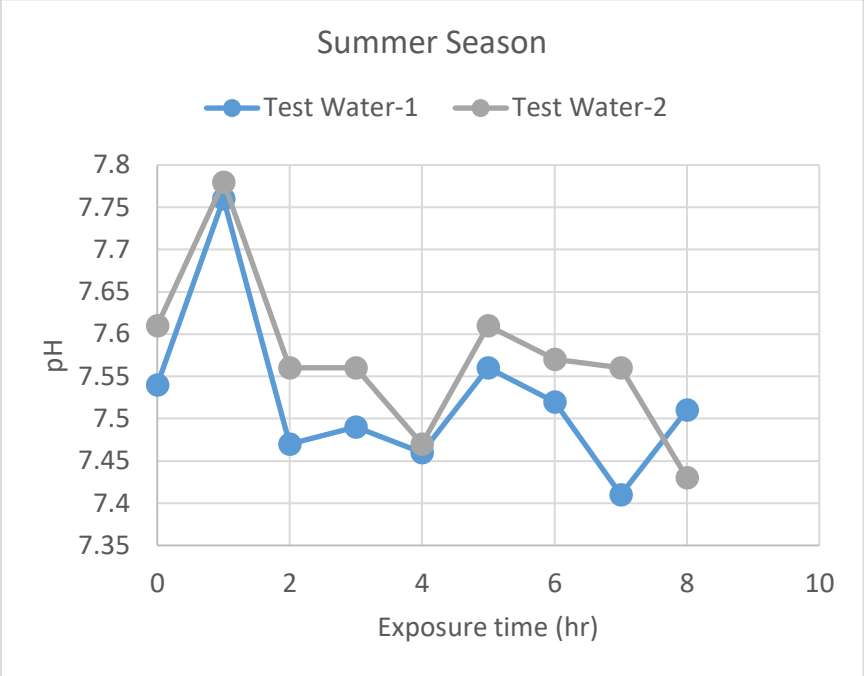

Figure 4. 1. pH vs Exposure time of solar irradiance (Summer Season)

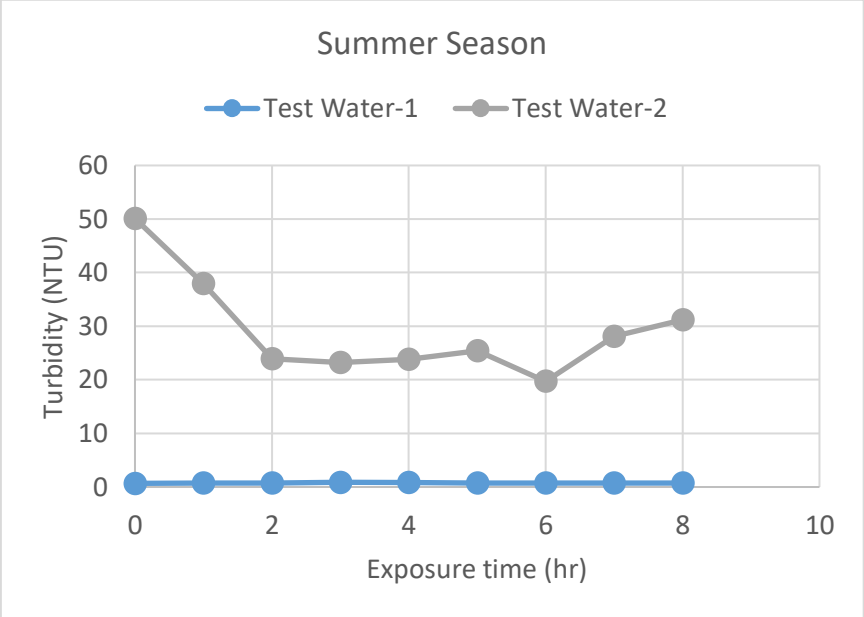

Figure 4. 2. Turbidity vs Exposure time of solar irradiance (Summer Season)

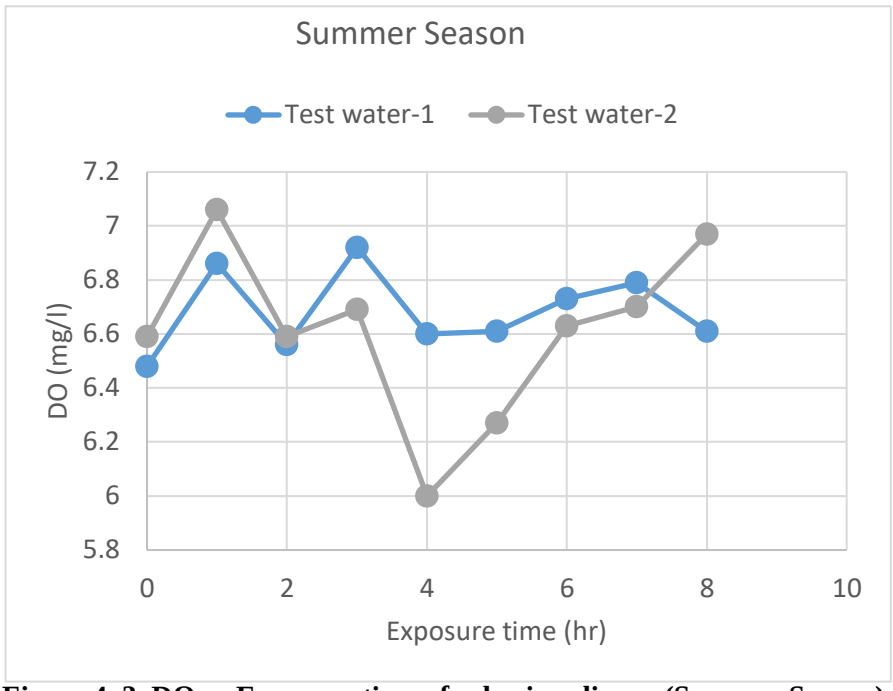

Figure 4. 3. DO vs Exposure time of solar irradiance (Summer Season)

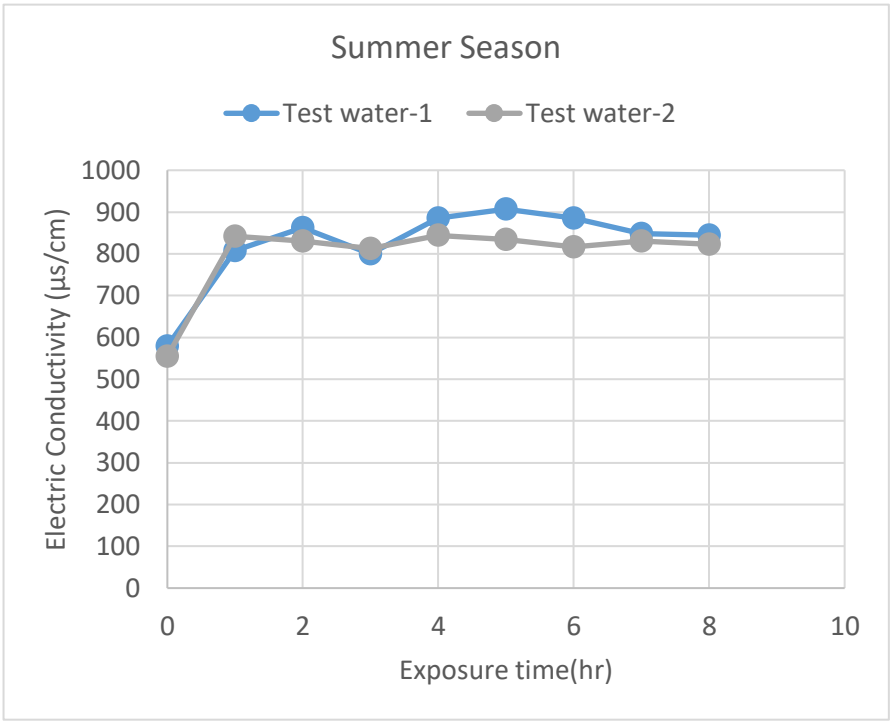

Figure 4. 4. EC vs Exposure time of solar irradiance (Summer Season)

From the figures it was observed that pH changes with time remains in range of 7.5-7.7 for all seasons data given in Appendix A.DO decreases with the elapse of exposure of solar irradiance because of the microbial inactivation occurred. It was also observed that the EC always raised after the solar exposure for both of the test waters. In terms of turbidity it was observed that it decreases simultaneously for the worst case test water-2 for all seasons. From the physicochemical data for two different seasons given in Appendix A we can observe that they don't vary much due to seasonal variation. But the experimental data show that value of turbidity decreases with increasing exposure to the sunlight, i.e. the value of turbidity for the first hour of exposure was 43.9 NTU for TW-2 but at the 8^{th} hour of exposure it decreased to 25 NTU. In the case for DO the value gradually increases.

4.3 Log Reduction Values (LRV) in different seasons

The experiment was based on data found during tests in various seasons. We observed a lot of variation in efficiency in killing E. coli due to the seasonal changes. . It was observed that for both types of test water the LRV value was greater than 4. According to WHO guideline, **for a LRV value of greater than 4 the technology is considered to be highly protective** in terms of bacteria removal. Hence it may be concluded that the filters are highly protective. In summer season we can achieve 0 bacterial count in 8 hours. For monsoon season to achieve satisfactory LRV value we need experimental modification i.e. foil paper and also exposure hour of 16 hours. Following tests over 500 mL sample water for each container with exposure ranging from a minimum of 8 hours to a maximum of 16 hours (2 days). A statistical analysis of paired t-test was performed to asses performance of SODIS in E. coli removal and found that we get a

minimum LRV of 2.62 without any experimental modification while a high LRV value of 5.4 can be achieved by SODIS using experimental modifications. In the experiment two types of containers were used to test sample water containing $5x10^6$ CFU/100 mL. Two types of water were used (TW-1 and TW-2). Test water-1(Turbidity <5 NTU, pH 7.0-9.0) and Test water-2(Turbidity >30 NTU, pH 6.0-10.0) were prepared following the WHO Guideline (2011) for laboratory verification of different Household Water Treatment method. The mean LRV for our experiments spanning the three seasons was 3.864. But with foil paper as experimental modification the LRV value has never gone below 4 which is the standard of highly protective sample water according to Performance requirement for HWT by WHO guideline.

4.3.1 Summer Season

In this season we have conducted experiment in PET bottle for 8-hour exposure without any modification but the bottles were laid on corrugated steel sheet. The Test water-1 and Test water-2 irradiance value with the reduction of bacterial growth are shown and also the temperature rising values were shown by using the pyrometer.

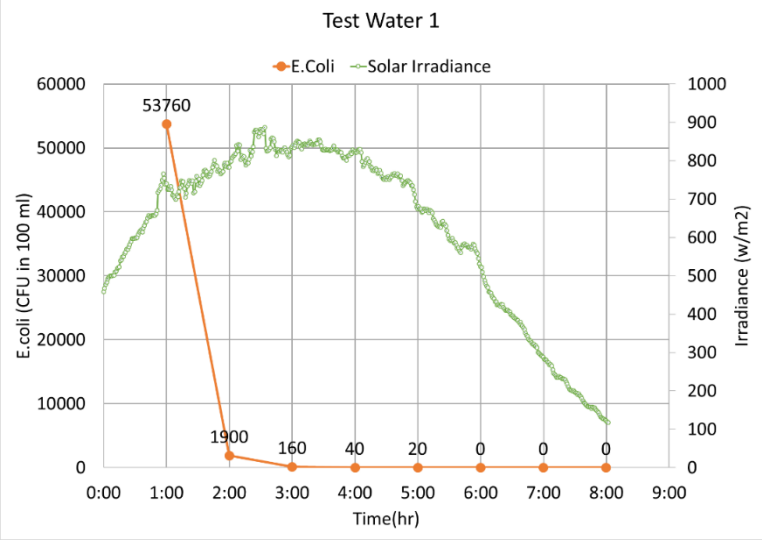

Figure 4. 5.Test water-1 bacterial inactivation in PET bottle 8 hour solar exposure (Summer Season)

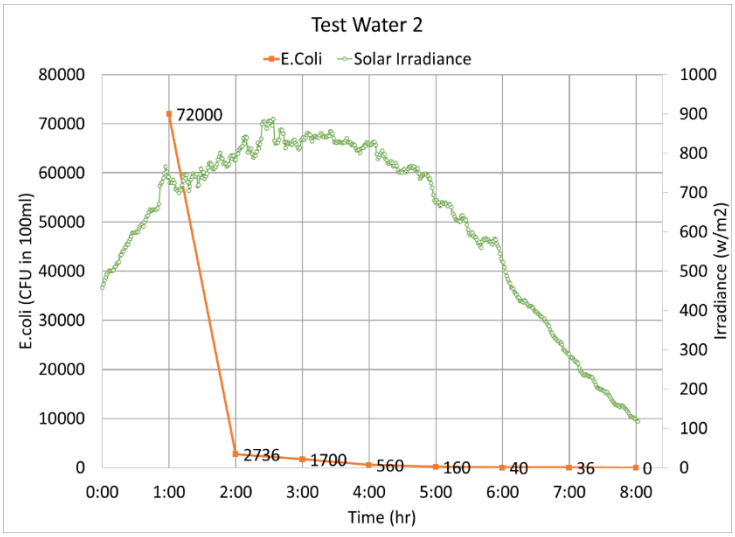

Figure 4. 6. Test water-2 bacterial inactivation in PET bottle 8 hour solar exposure (Summer Season)

From the figure we saw that the bacteria inactivation occurs within 4 hours in TW-1 and 8 hours in TW-2. In summer, the experiment is efficiency is more without using any modification. If we use foil paper, then we will get more efficiency in the destruction of bacteria.

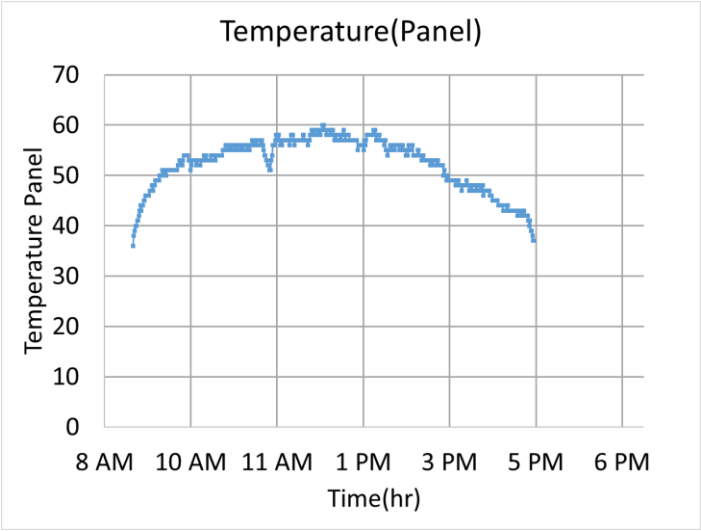

Figure 4. 7. 8-hour solar exposure temperature variation (Summer Season)

The temperature raised in this season is 61˚C at 12 P.M which is high enough to destroy pathogens causing microbiological contaminated diseases. In corrugated steel sheet the temperature remains stable for a long time so it is enough to use it in this season

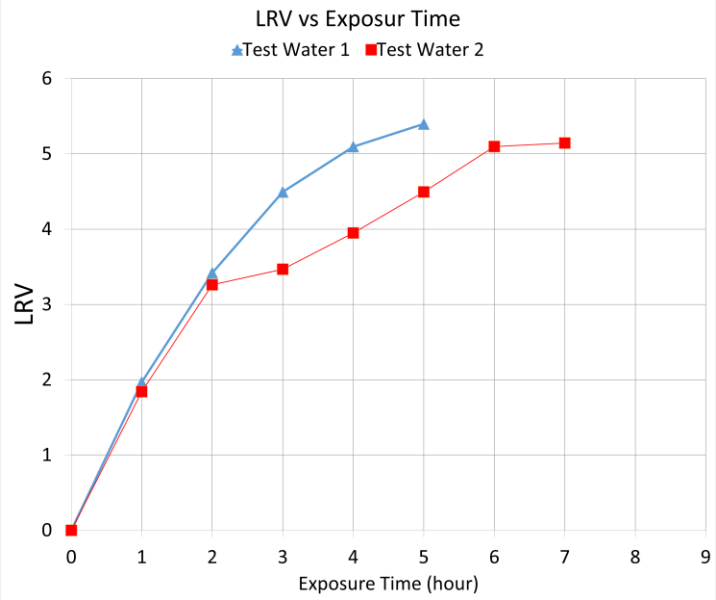

Figure 4. 8. LRV in PET bottle 8 hour solar exposure (Summer Season)

The LRV value obtain was 5.4 in Test water-1 which is highly protective according to the WHO guideline for HWT technologies. Test water-2 which is the worst case condition of sample also shows 4.78 LRV in the environmental created in corrugated steel sheet.

4.3.2 Monsoon Season

In this season we faced a challenge for the SODIS experiment since the weather is cloudy and so we have to increase our exposure hour to 16 hours and also use experimental modification like foil paper which is laid on corrugate steel sheet. The test water value of bacterial inactivation in this season for different containers along with modification were shown in this section.

4.3.2.1 PET bottle without foil paper

The experiment conducted in this section is in PET bottle which is kept in solar exposure for 8 hours and the results in test water-1 and test water-2 is shown.

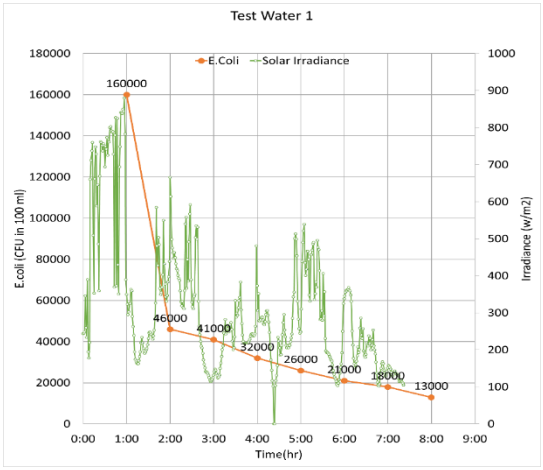

Figure 4. 9. Test water-1 bacterial inactivation in PET bottle 8 hour solar exposure (Monsoon Season)

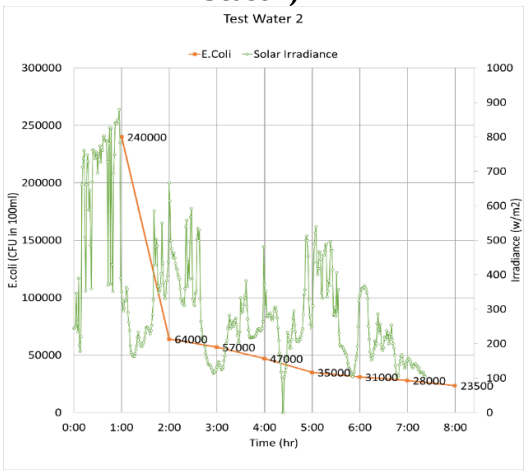

Figure 4. 10. Test water-2 bacterial inactivation in PET bottle 8 hour solar exposure (Monsoon Season)

The solar irradiance is irregular as shown in the figure and so there is 13000 CFU/100ml of bacteria after 8-hour exposure and so the experiment is not feasible for the above conditions. In test water-2 the presence of bacteria is 23500 CFU/100ml after 8 hours which is a huge number of bacteria and the condition is not suitable for the experiment

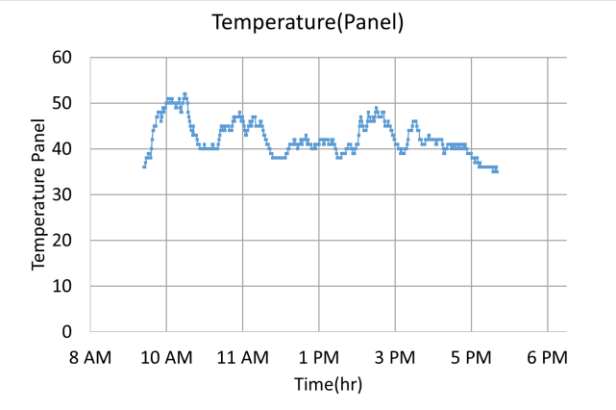

Figure 4. 11. 8 hour solar exposure temperature variation (Monsoon Season)

The temperature varies gradually for different duration of time and so the bacteria is not properly destroyed.

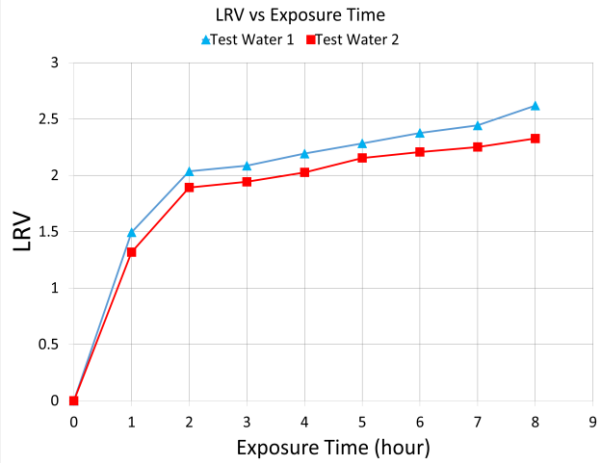

Figure 4. 12. LRV in PET bottle 8 hour solar exposure (Monsoon Season)

The LRV is low which is 2.6 in test water-1 and not protective according to the WHO guideline for HWT technologies. In test water-2, it is low than even test water-2. In monsoon season using PET bottle in 8-hour solar exposure the bacterial inactivation is not safe since the bacteria remains after the treatment period.

4.3.2.2 Plastic Bag without foil paper

Plastic bag results shown here indicate a huge reduction of bacteria within 8 hours the bacteria count becomes 1000 CFU/100ml in test water -1 and in test water-2 it come 25000 CFU/100ml.

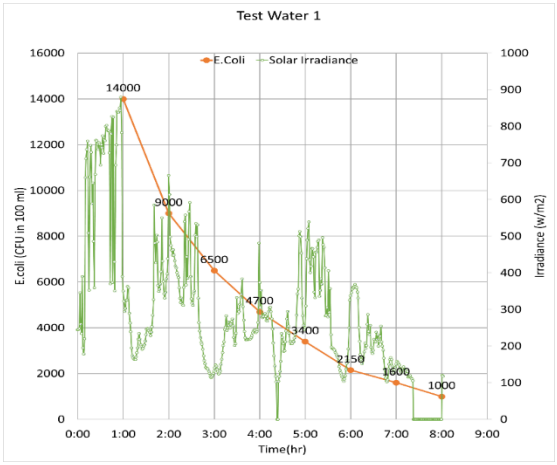

Figure 4. 13. Test water-1 bacterial inactivation in Plastic bag 8 hour solar exposure (Monsoon Season)

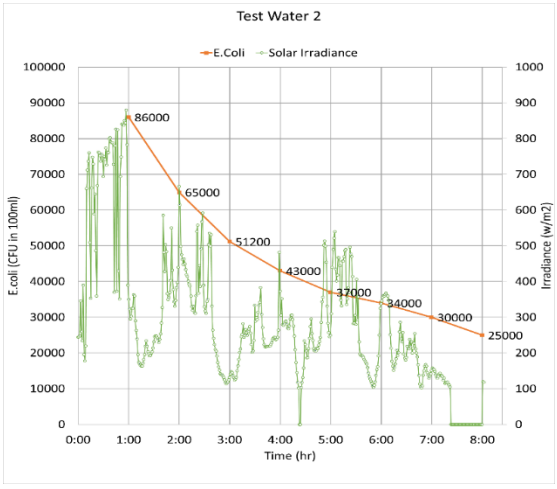

Figure 4. 14. Test water-2 bacterial inactivation in Plastic bag 8-hour solar exposure (Monsoon Season)

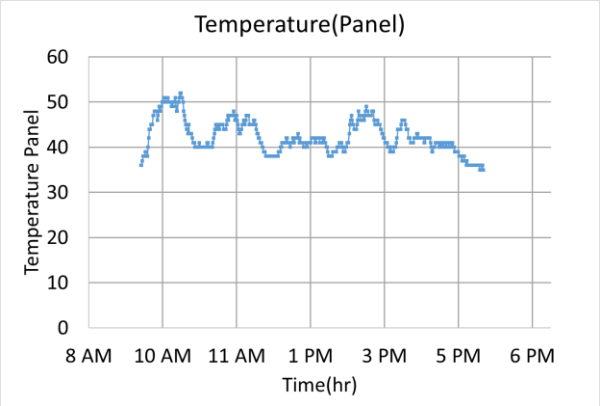

Figure 4. 15. 8-hour solar exposure temperature variation (Monsoon Season)

Though the temperature is not regular but the inactivation of bacteria occurs more than in PET bottle in 8-hour exposure of solar irradiance.

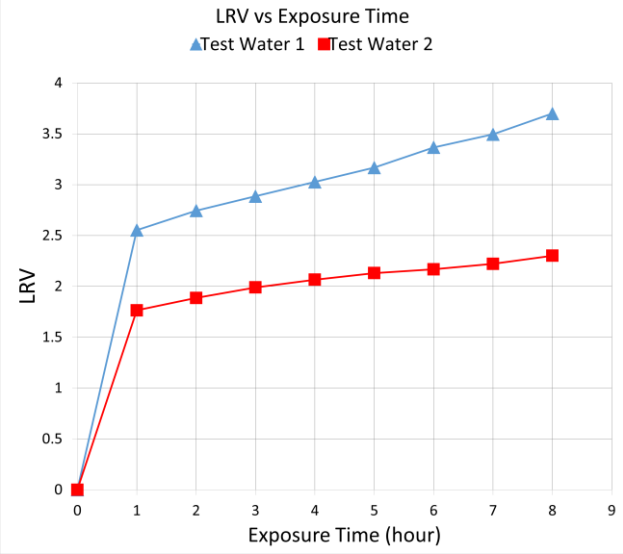

Figure 4. 16. LRV in Plastic bag 8-hour solar exposure (Monsoon Season)

The LRV value for test water-1 is 3.65 which is Protective declared by the WHO guideline for HWT technologies and for test water-2 the LRV is 2.4 which is a lot less. If the water is test water-1 then the experiment conducted by this way will be count as Protective to drink the water.

4.3.2.3 PET bottle with foil paper

PET bottle being laid with foil paper on corrugated steel sheet for 16 hour and the results shown.

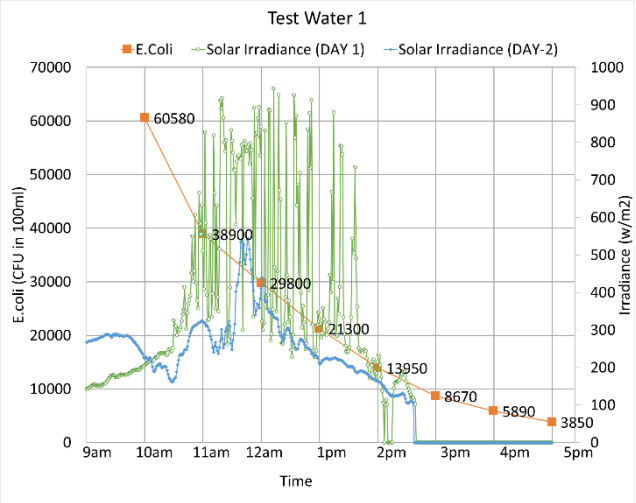

Figure 4. 17. Test water-1 bacterial inactivation in PET bottle with foil paper 16-hour solar exposure (Monsoon Season)

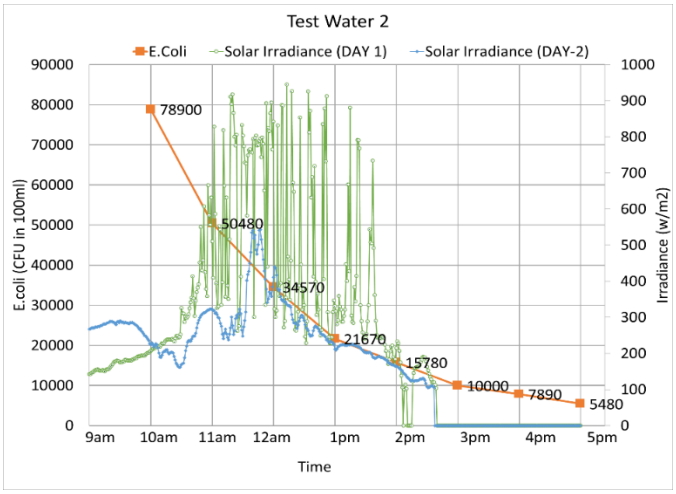

Figure 4. 18. Test water-2 bacterial inactivation in PET bottle with foil paper 16-hour solar exposure (Monsoon Season)

There is a more inactivation of bacteria in test water-1 and is 3850 CFU/100ml and it gives better results by using foil paper as a modification in this season. Furthermore, in test water-2 the bacterial inactivation count is 5480 CFU/100 ml after 16hour exposure of solar irradiance.

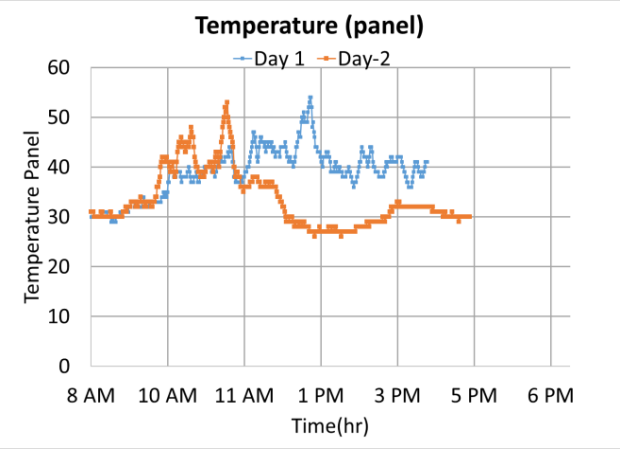

Figure 4. 19. 16-hour solar exposure temperature variation (Monsoon Season)

The temperature risen during day-1 is more than in day-2 and the highest temperature is 56˚C which kills off most of the pathogens causing diseases.

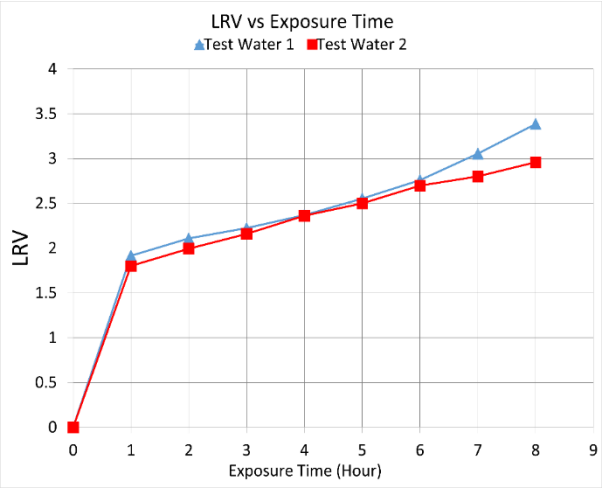

Figure 4. 20. LRV in PET bottle with foil paper 16-hour solar exposure (Monsoon Season)

The LRV for test water-1 is 3.38 which is a lot better than previous experiment conducted without using foil paper. Moreover, in test water-2 the value is 2.99 which is also more significant. According to WHO guideline for HWT technologies the process is termed as Protective.

4.3.2.4 Plastic Bag with foil paper

Plastic bag shows the best results for monsoon season when conducted for 16-hour exposure along with foil paper.

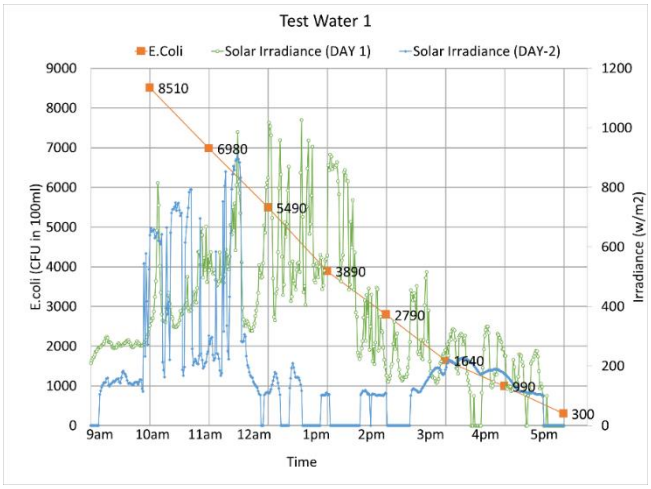

Figure 4. 21. Test water-1 bacterial inactivation in Plastic bag with foil paper 16-hour solar exposure (Monsoon Season)

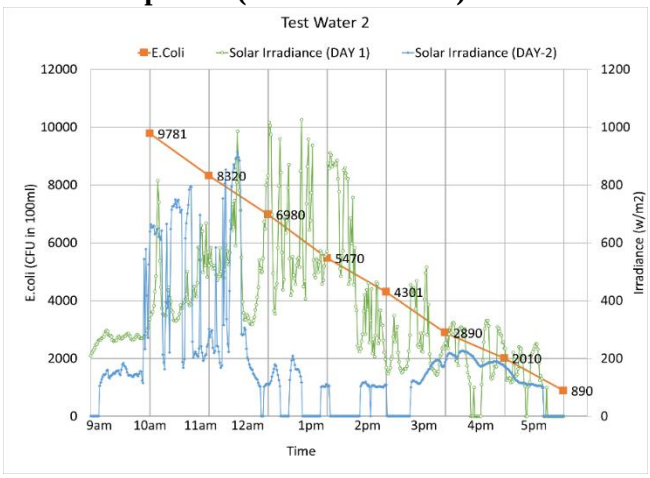

Figure 4. 22. Test water-2 bacterial inactivation in Plastic bag with foil paper 16-hour solar exposure (Monsoon Season)

The bacteria count is 300 CFU/100ml in test water-1 after 16-hour exposure which is the highest reduction of bacteria in monsoon period and also recommended to use this way of process in this season. Test water-2 bacteria count is also less which is 890 CFU/100ml.

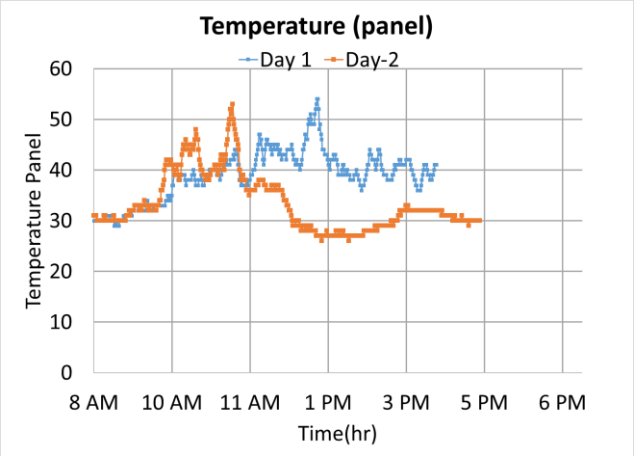

Figure 4. 23. 16-hour solar exposure temperature variation (Monsoon Season)

The temperature being raised among the 16 hr. exposure is 56˚C and is capable of disinfection harmful bacteria.

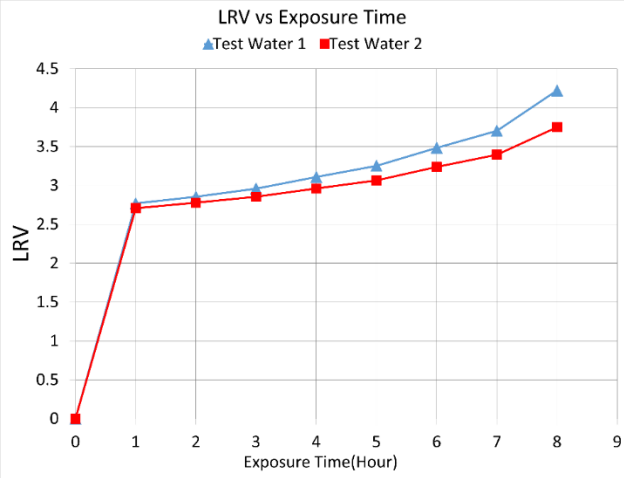

Figure 4. 24. LRV in Plastic bag with foil paper 16-hour solar exposure (Monsoon Season)

The LRV value is the highest in monsoon season in test water-1 which is 4.22 which is Highly Protective as declared by the WHO guideline for HWT technologies. And also in test water-2 the LRV is 3.74 which is Protective respectively.

4.3.3 Winter Season

In this season the sun rises early but the solar irradiance at our location reaches lately and the solar irradiance diminishes early too. But the bacterial inactivation in test waters continue because of the UV-A radiation. The values of different test with modification is given.

4.3.3.1 PET bottle with foil paper

PET bottle laid on corrugated steel sheet along with foil paper and shows good results within 8 hour exposure time

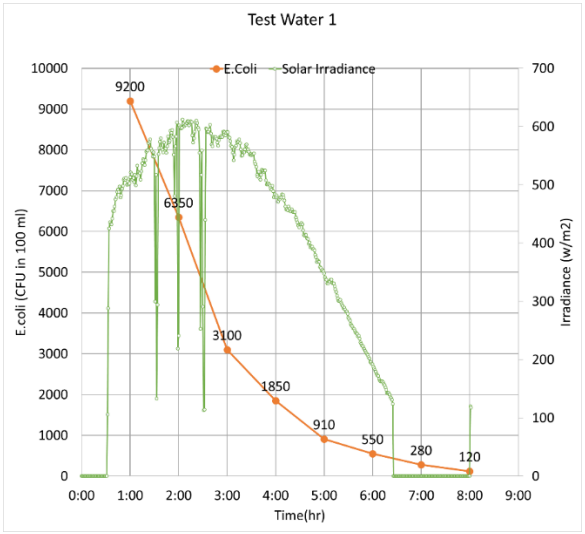

Figure 4. 25. Test water-1 bacterial inactivation in PET bottle with foil paper 8-hour solar exposure (Winter Season)

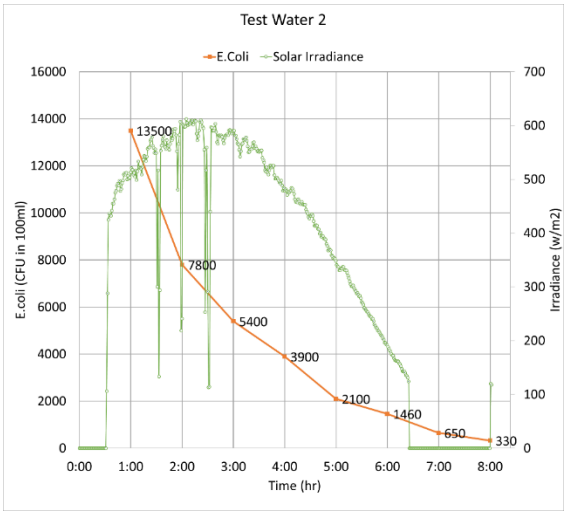

Figure 4. 26. Test water-2 bacterial inactivation in PET bottle with foil paper 8-hour solar exposure (Winter Season)

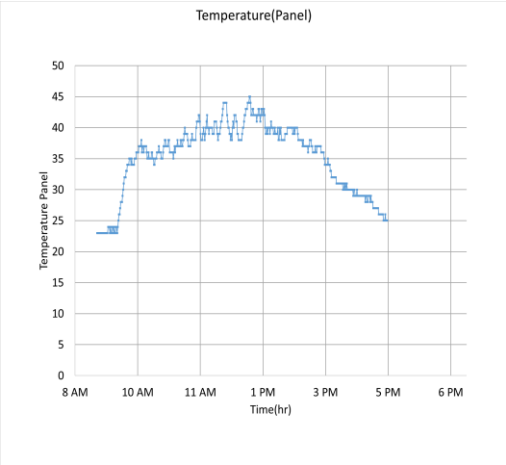

Figure 4. 27. 16-hour solar exposure temperature variation (Winter Season)

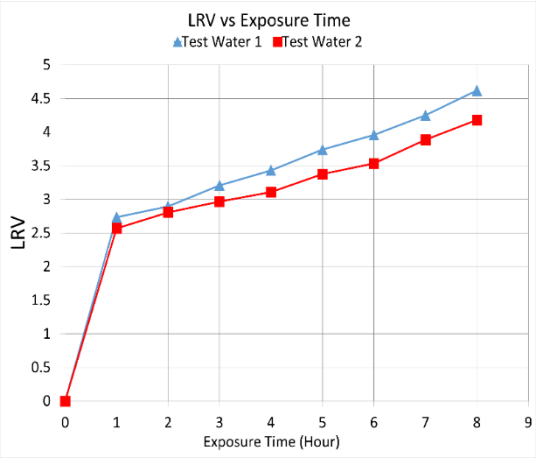

Figure 4. 28. LRV for 16-hour solar exposure (Winter season)

The temperature raised within the duration is 45˚C and the LRV value is 4.6198 in test water-1 which is Highly protective according to WHO guideline for HWT technologies and also in test water-2 the LRV is 4.2 which is also Highly Protective respectively.

4.3.3.2 Plastic bag with foil paper

Plastic bag experiments show more efficient results as shown here for 8-hour exposure.

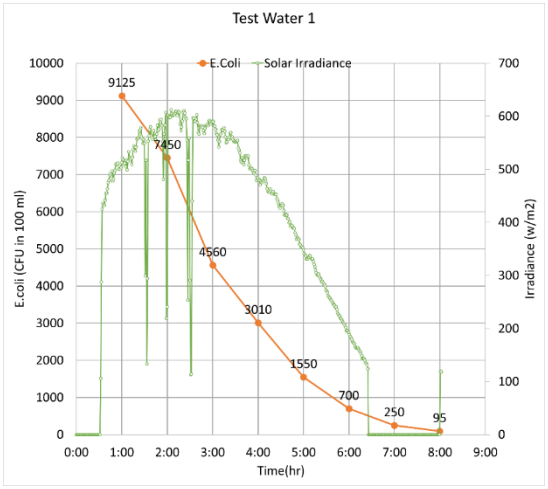

Figure 4. 29. Test water-1 bacterial inactivation in Plastic bag with foil paper 8 hour solar exposure (Winter Season)

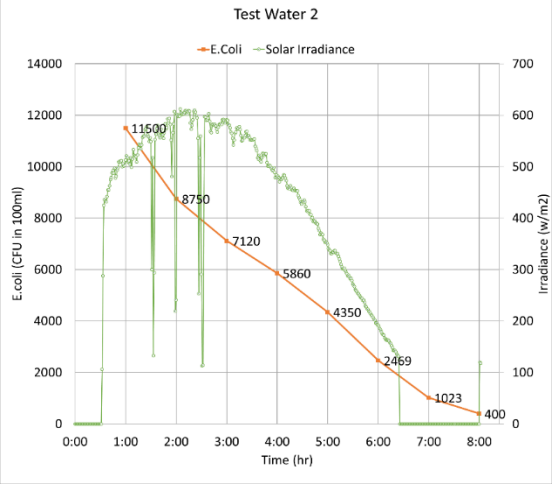

Figure 4. 30. Test water-2 bacterial inactivation in Plastic bag with foil paper 8-hour solar exposure (Winter Season)

In test water-1 after 8-hour exposure of solar irradiance the bacterial inactivation went down to 95 CFU/100ml and in test water-2 it went down to 400 CFU/100ml which is a great result for this season

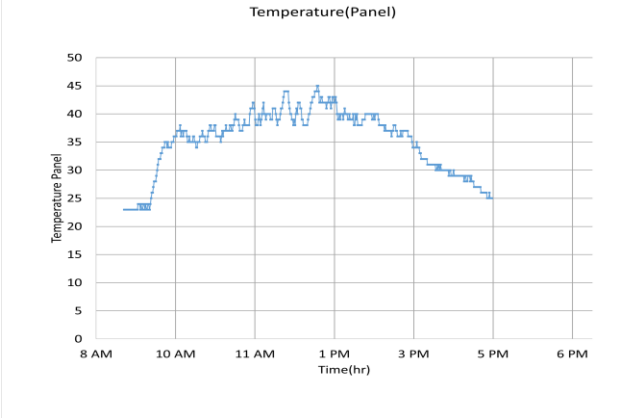

Figure 4. 31. 8-hour solar exposure temperature variation (Winter Season)

The temperature is 45˚C raised in the experiment conducting day and it can destroy pathogens too and effective for the winter season.

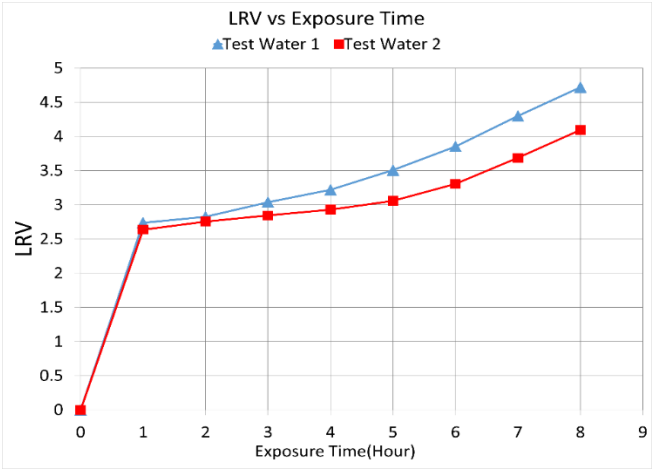

Figure 4. 32. LRV in Plastic bag with foil paper 8-hour solar exposure (Winter Season)

The LRV is highest for the winter season and which is 4.712 for test water-1 and for test water-2 the LRV is 4.12 and both the test water shows Highly Protective nature according to the WHO guideline for HWT technologies.

4.3.4 Evaluation of all seasons data

From the tested data, a table has been formed which categorizes based on various container with or without experimental modification and exposure hour. The table follows WHO guideline for performance requirement for HWT. The result found shows that, during summer season we can achieve LRV of 5.4, which is highly protective according to WHO guideline by using the commonly used procedure.

Table 4. 1. WHO guideline for performance requirement for HWT

Pathogen class	Log_{10} reduction required[b]		
	Interim	Protective[c]	Highly[c] protective
	Requires correct, consistent and continuous use to meet performance levels		
Bacteria	Achieves "protective" target for two classes of pathogens and results in health gains	≥ **2**	≥ **4**
Viruses		≥ **3**	≥ **5**
Protozoa		≥ **2**	≥ **4**

Performance requirement for HWT

But during monsoon season to achieve highly protective standards we need Plastic bag as containers as well as foil paper as experimental modification. Because, foil paper acts as an amplifier for sunlight also it reflects the sunlight back to the sample water which increases SODIS efficiency.

Table 4. 2. Evaluation of all seasons data.

Season	Container Type	Exposure Time (hr)	Experimental Modification Material	Log Reduction Value (LRV)	Performance Level
Summer	PET	8	N/A	5.4	Highly Protective
Monsoon	PET	8	N/A	2.62	Protective
	Plastic Bag	8	N/A	3.7	Protective
	PET	16	Foil Paper	3.38	Protective
	Plastic Bag	16	Foil paper	4.22	Highly Protective
Winter	PET	8	Foil paper	4.6198	Highly Protective
	Plastic Bag	8	Foil paper	4.721	Highly Protective

Plastic bag due to their larger area exposed to sunlight and smaller water depth increases disinfection efficiency. So, it is highly recommended to use Plastic bag and use foil paper as experimental modification during monsoon and winter season.

4.4 Regrowth of microorganisms

The regrowth of bacteria occurs in all seasons after a while of time and from the results shown we will recommend to drink the water with 12 hr elapse time of the SODIS experiment run down.

Table 4. 3. Regrowth of microorganisms.

Season	Container Type	Exposure time (hours)	Experimental Modification Material	Criteria	Hour	E.coli count (CFU/100ml)	
						Test water-1	Test water-2
Summer	PET	8	N/A	Solar exposure value of E.coli	8	0	0
				Incubation of E.coli in Dark Environment	12	170	260
					24	1200	1700
Monsoon	Plastic Bag	8	N/A	Solar exposure value of E.coli	8	300	890
				Incubation of E.coli in Dark Environment	12	6890	8950
					24	18539	25440
Winter	Plastic Bag	8	Foil Paper	Solar exposure value of E.coli	8	95	400
				Incubation of E.coli in Dark Environment	12	700	2500
					24	10650	19860

In summer and winter season the bacterial regrowth rate is less but in monsoon the bacterial regrowth occurs more rapidly because the presence of bacteria after the SODIS experiment run.

4.5 Weibull Inactivation Model

Application of Weibull inactivation model to determine required time for bacterial inactivation. The model was done using test data. From the tests done during summer and monsoon season, the results clearly indicate that during summer season PET bottles and plastic bags both containers can achieve highly protective in accordance with WHO Household Water Treatment performance standards. While in monsoon season, only Solar Disinfection done for 16-hour solar exposure done with plastic bag and using foil paper as experimental modification is able to achieve highly protective standards.

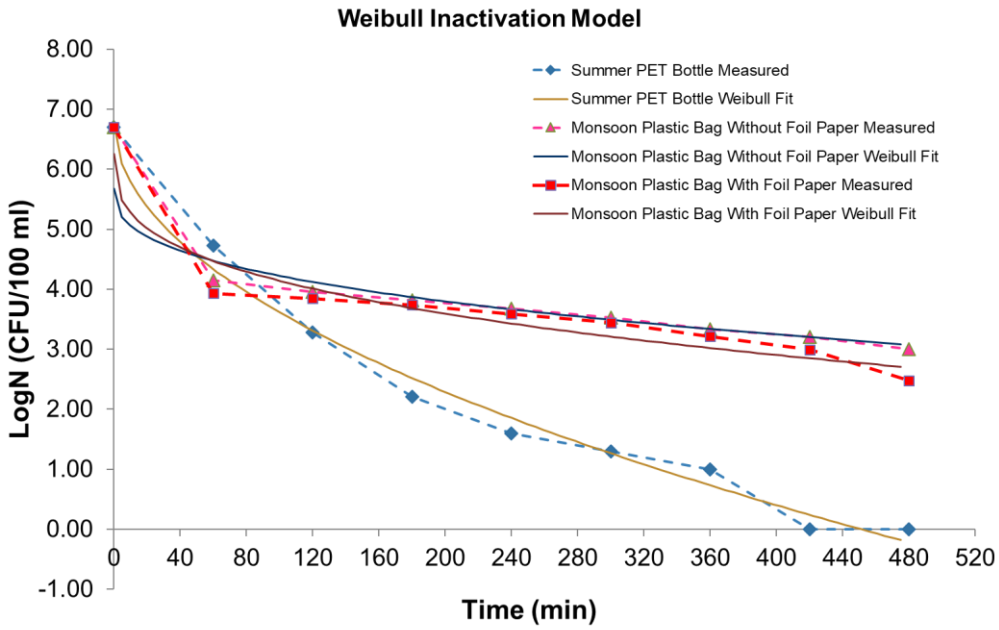

Figure 4. 33. Weibull bacterial inactivation model of study data

Weibull inactivation model used in this experiment determines the time required in hours for 4 log reduction of bacteria in the sample waters. Using this model and comparing test data with

irradiance value on that day, exposure time required for 4 log reduction (which is highly protective in accordance to WHO guideline) can be determined for each sample water.

Table 4. 4. Weibull bacterial inactivation model data generated.

Weibull distribution survival model											
Season	Container Type	Exposure Time (hr)	Experimental Modification Material	Delta, (min)	p	$logN_0$ (CFU/100ml)	Root MSE	R^2-(adj)	4 log (99.99%) removal per intensity and model time required		
									Solar Intensity (W/m2)		Weibull model required time (hr)
									Min	Max	
Summer	PET	8	N/A	10.41	0.51	6.77	0.2898	0.983	118	887	3
Monsoon	PET	8	N/A	6.87	0.22	6.7	0.0838	0.989	102	880	62
	Plastic Bag	8	N/A	36.27	0.37	5.68	0.4443	0.937	102	880	25
	PET	16	Foil Paper	10.24	0.29	6.68	0.1854	0.963	100	970	20
	Plastic Bag	16	Foil paper	10.47	0.33	6.26	0.3433	0.917	100	970	11.5
Winter	PET	8	Foil paper	30.69	0.48	5.91	0.4097	0.908	100	612	9.5
	Plastic Bag	8	Foil paper	3.89	0.3	6.66	0.3021	0.95	100	612	6.58

$$t = (LRV)^{\frac{1}{p}} * \partial \quad \text{Where LRV} = \frac{Log\ No}{Log\ N} = 4$$

The least amount of time required for 4 log reduction is 160.0258838 minute or 2.6 hours for PET bottle without any experimental modification where irradiance was 620.43064 W/m^2.While the longest time required is 3746 minute or 62 hours with irradiance 314.9115646 W/m^2 for monsoon season PET bottle sample without experimental modification (which is not feasible).So for monsoon season it is advised to use foil paper and plastic Bag for SODIS with exposure hour of minimum 698.828 min or 11.65 hours.

4.6 Statistical Analysis

In order to find the significant value and process of the SODIS experiment conducted we have done statistical analysis of the data we have found after conducting our experiment. We have don't paired t-test and ANOVA test to find the significance of process.

4.6.1 Paired t-test

Paired t- test done between two process to find the more significant processes and the analysis is shown here.

4.6.1.1 Foil paper and Tin sheet between Plastic Bag

We wanted to find the better process between foil paper and tin sheet experiment conduction and the value taken here,

H_0: Foil paper = Tin sheet

H_1: Foil paper > Tin sheet

Table 4. 5.Foil paper and tin sheet bacterial reduction data

Hour	E.coli (CFU/100ml) of Foil Paper	E.coli (CFU/100ml) of Tin Sheet
1:00	7570	14000
2:00	6430	9000
3:00	5260	6500
4:00	3470	4700
5:00	2360	3400
6:00	1090	2150
7:00	240	1600
8:00	10	1000

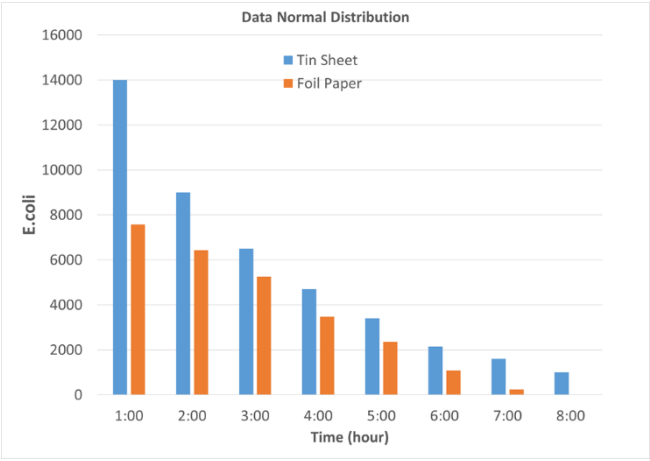

Figure 4. 34. Data normally distributed results.

The data set used for the analysis is given here and the data is normally distributed shown in the figure 4.34.

Table 4. 6. Paired t test table for foil paper and tin sheet

t-Test: Paired Two Sample for Means		
	E.coli (CFU/100ml) of Tin Sheet	*E.coli (CFU/100ml) of Foil Paper*
Mean	5293.75	3303.75
Variance	19556026.79	8265083.929
Observations	8	8
Pearson Correlation	0.957327917	
Hypothesized Mean Difference	0	
df	7	
t Stat	3.017577081	
P(T<=t) one-tail	0.009726383	
T Critical one-tail	1.894578605	

From the results we see that P value < 0.05. So Foil paper is more significant than Tin sheet.

4.6.1.2 Bottle and Plastic Bag

Paired t-test conducted between bottle and plastic bag here and the dataset used here is shown and the data is normally distributed shown in the figure 4.35. The values taken here,

H_0: PET Bottle = Plastic Bag

H_1: Plastic Bag > PET Bottle

Table 4. 7.Bottle and plastic bag bacterial reduction data

Hour	E.coli (CFU/100ml) of BOTTLE	E.coli (CFU/100ml) of Plastic Bag
1:00	49900	9460
2:00	35200	7430
3:00	18500	6120
4:00	12200	4980
5:00	6500	3760
6:00	2500	2490
7:00	2550	1670
8:00	2600	960

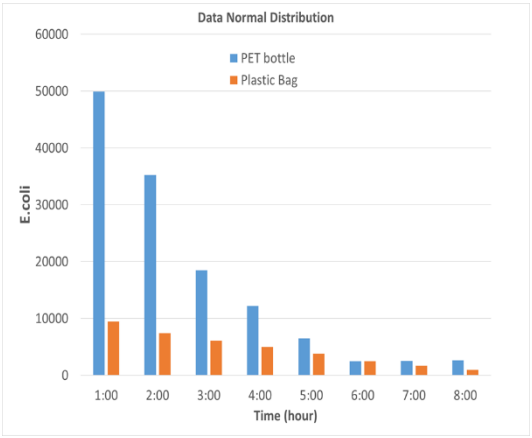

Figure 4. 35. Data normally distributed results.

Table 4. 8. Paired t test table for bottle and plastic bag

t-Test: Paired Two Sample for Means		
	E.coli (CFU/100ml) of BOTTLE	*E.coli (CFU/100ml) of Plastic Bag*
Mean	16243.75	4608.75
Variance	310146741.1	8724983.929
Observations	8	8
Pearson Correlation	0.95040907	
Hypothesized Mean Difference	0	
df	7	
t Stat	2.218746922	
P(T<=t) one-tail	0.030995894	
t Critical one-tail	1.894578605	

From the results, P value < 0.05. So Plastic Bag is more significant than PET Bottle.

4.6.2 ANOVA test

The test is done between different seasons data to find the more significance season among them.

The ANOVA single factor test were run by the shown dataset. The values taken here,

H0: $\mu 1 = \mu 2 = \mu 3$ or Summer = Monsoon = Winter

H1: at least one of the means is different.

Table 4. 9. 3 Seasons data.

Hour	E.coli (CFU/100ml) of Summer	E.coli (CFU/100ml) of Monsoon	E.coli (CFU/100ml) of Winter
1	53760	60580	9200
2	1900	38900	6350
3	160	29800	3100
4	40	21300	1850
5	20	13950	910
6	0	8670	550
7	0	5890	280
8	0	3850	120

Table 4. 10. ANOVA single factor test results.

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	8	55880	6985	3.58E+08		
Column 2	8	182940	22867.5	3.8E+08		
Column 3	8	22360	2795	10960314		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between	1.79E+09	2	8.97E+08	3.594004	0.04546	3.4668
Within Gr	5.24E+09	21	2.5E+08			
Total	7.03E+09	23				

From the results we found that if F > F crit, we reject the null hypothesis. This is the case, 3.594004 > 3.4668. Therefore, we reject the null hypothesis. The means of the three seasons are not all equal. At least one of the means of the season are different. So the Summer, Monsoon and Winter season are different according the analysis done here and also the P value is less than .05 which show the significance of the analysis is right.

The experiments clearly indicate that Solar Disinfection (SODIS) is applicable for bacterial disinfection as a household water treatment method. In summer season it can be run in PET bottle without any required modifications as per our observations. But during monsoon season it is highly advised to use plastic bag as a container and use foil paper under the bags left for Solar Disinfection with 16 hours (2 days) solar exposure. It must be mentioned that for rural areas where foil paper may not be available, SODIS is still highly recommended as it reaches the protective standards of WHO guideline without the mentioned modifications.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study is to have a proper knowledge about the efficiency of SODIS in Bangladesh weather conditions. In this study, the main focus was to find the bacterial inactivation, regrowth of microorganisms and model application to assess the required time for solar disinfection. The data collection was carefully done before analyzing the output. The model analysis showed significant efficiency in bacterial inactivation occurs for summer season which will take only 3hr to get 4 log reduction whereas in monsoon season a significant decrease in bacteria occurs by using foil paper laid on corrugated steel sheet in plastic bag which would take only 11.50hr to get 4 log reduction and further in winter season by using the same procedure in it would take about 6.58hr to get 4 log reduction. In case of cloudy weather, the experiment should be continued for two days or 16hour exposure of solar irradiance which will significantly decrease the bacterial count. However, the efficiency of SODIS is more by using foil paper and plastic bag which is analyzed by statistical analysis. There is no significant change physicochemical data of test waters in all seasons but there is a slight change in turbidity of test water-2 which is considered as the worst case scenario of ground water. From this study, it is also seen that from all seasons summer season is the best time for getting efficient SODIS results and recommended to drink the water before 12hr elapse of time of the experiment run.

Further studies are recommended to be conducted in which to eliminate the bacterial regrowth some additives should be injected into the water such that the additive did not show any harmful effects to the drinker and significantly accelerate the SODIS process. Furthermore, more amplifier of the process can be included like solar collection system, sand as a amplification of the solar irradiance and so on. Moreover, different microorganisms should be injected into the test waters for checking the inactivation of microorganisms with time and solar irradiance. This chapter gives an overview of the important findings of this research. Identifying the bacterial inactivation and regrowth of microorganisms and the required time of solar irradiance could have a wide range of applications in safe drinking water, health and new efficient technologies for household water treatment.

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APPENDIX A

Physicochemical data of all seasons in Bangladesh done in different containers and in different environmental modification.

❑ **Summer Season Data for PET bottle**

TW-1 = Test Water -1
TW-2 = Test Water -2

Table of Physicochemical Data

Date:25/4/19			Exposure Time (Hour)															
	Before Treatment		1		2		3		4		5		6		7		8	
	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2
Turbidity (NTU)	0.68	50.1	0.77	38	0.76	23.9	0.88	23.2	0.84	23.8	0.74	25.4	0.7	19.7	0.71	28.1	0.72	31.2
pH	7.54	7.61	7.76	7.78	7.47	7.56	7.49	7.56	7.46	7.47	7.56	7.61	7.52	7.57	7.41	7.56	7.51	7.43
Temp (˚C)	28.4	28.4	34.6	37.2	36.1	39.6	41.2	45.6	43.7	43.2	46.4	41.2	46.6	40.5	44.4	39	38.5	37.8
DO (mg/l)	6.48	6.59	6.86	7.06	6.56	6.59	6.92	6.69	6.6	6	6.61	6.27	6.73	6.63	6.79	6.7	6.61	6.97
EC (µs/cm)	579	555	808	842	863	830	800	813	886	844	907	835	886	816	849	830	844	823

❑ **Monsoon Season Data for Plastic Bag**

TW-1 = Test Water -1
TW-2 = Test Water -2

Table of Physicochemical Data

Exposure Hour	Initial		1		2		3		4		5		6		7		8	
Test Water type	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2
Turbidity (NTU)	1.08	43.9	0.99	31	0.76	23.8	0.93	23.2	1.1	21.4	1.12	19.2	1.09	24	1.21	23	1.03	25
pH	7.65	7.6	7.78	7.74	7.86	7.93	7.86	7.98	7.92	7.79	7.86	7.9	7.96	7.96	7.92	7.8	7.24	7.26
Temp (˚C)	28.4	28.4	34.9	38.1	36.6	38.7	41.6	43.2	43.1	42.2	45.5	41.69	44.3	41.1	42.3	39.5	38	37.6
DO (mg/l)	6.2	6.5	6.83	6.63	6.83	6.62	6.62	6.56	6.44	6.43	6.32	6.29	6.3	6.16	6.25	6.21	6.46	6.7
EC (µs/cm)	740	551	791	789	788	779	785	779	794	809	797	789	798	778	802	808	805	855

❑ **Winter Season Data for PET bottle**

TW-1 = Test Water -1
TW-2 = Test Water -2

Table of Physicochemical Data

Date:07/10/2019	Before Treatment		Exposure Time (Hour)															
			1		2		3		4		5		6		7		8	
	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2	TW-1	TW-2
Turbidity (NTU)	1.7	48.5	1.3	35.6	0.85	31	0.76	25.5	0.9	24.6	1.1	21.1	1.03	20.9	1.15	23	1.06	24
pH	7.6	7.65	7.75	7.71	7.82	7.82	7.89	7.86	7.88	7.9	7.82	7.83	7.9	7.93	7.82	7.79	7.3	7.41
Temp (˚C)	29	28.5	35.5	38.5	37.5	39.8	40.9	42.6	44.5	46.5	47.8	45.5	44.2	41.2	43.2	41.5	39.5	38.5
DO (mg/l)	6.8	7.33	6.86	6.63	6.89	6.62	6.71	6.56	6.51	6.43	6.46	6.29	6.41	6.16	6.35	6.21	6.45	6.44
EC (µs/cm)	740	551	791	789	788	779	785	779	794	809	797	789	798	778	802	808	805	1013